Concrete Coefficient Of Thermal Expansion Testing

State of California Department of Transportation
Office of Concrete Pavements and Pavement Foundations
Division of Maintenance
5900 Folsom Blvd. MS#5
Sacramento, CA 95819

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Purpose

The purpose of the study was to assess what values Caltrans is achieving for concrete coefficient of thermal expansion (CoTE) on construction contracts and whether there are sufficient aggregate sources to achieve the AASHTO recommended CoTE value of 5.5. Also, what is the impact to the pavement design of higher values in order to determine if it is important to measure CoTE for pavement construction. The study has shown that higher values of CoTE have a negative impact on long-term pavement performance.

Background

Caltrans is adopting Mechanistic-Empirical (M-E) Pavement Design for concrete pavements. M-E pavement design provides the means to predict the performance and durability of pavement using numerical models. CoTE is one of the factors to consider in the design of concrete pavements. Research has shown that the CoTE of a pavement can impact its performance. M-E Design has included CoTE data as an input. CoTE data can be used to help insure that what is built meets the performance intent from design during construction.

The new pavement design methodology uses CoTE as an input. It is important to know the variation and acceptance criteria for this factor. The CoTE can be used to improve concrete joint design, calculate stresses, joint sealant design, and selecting sealant materials.

CoTE is measured of the change in length of concrete specimens subjected to changes in temperatures, using AASHTO T 336, "Standard Test Method for Coefficient of Thermal Expansion of Hydraulic Cement Concrete."

The test method determines the CoTE of a cylindrical concrete specimen with nominal dimensions of a 4-inch diameter and a 7-inch length. The specimen is maintained in a saturated condition and tested by measuring the length change of the specimen over a specified temperature range (50°F to 122°F). Length changes are measured using a submersible linear variable differential transformer (LVDT).

The CoTE is calculated according to the following formula:

$$CoTE = (\Delta L_a / L_0) / \Delta T$$

Where: ΔL_a = length change of specimen, L_0 = initial measured length of specimen, and ΔT = temperature change.

Summary of Coefficient of Thermal Expansion Test Results

The results of coefficient of thermal expansion testing performed in 2012 and 2013 are summarized in Table 1. The overall average and average for each district are shown in Table 2. Table 3 is a summary by project. The overall result for each aggregate source is shown in the report figures. A typical data sheet from the testing laboratory shows the required inputs for calculating the sample results.

Table 1 Summary by Quarry

Source Project EA	No. of Samples	Lowest Value	Highest Value	Ave με/°F	Standard Deviation	*Geologic Code
D01 91-23-0015 (HARRIS QUARRY) 01-480504	2	5.167	5.389	5.278	0.157	KJf
D02 91-47-0016 (UPTON MINE) 02-3E7604	5	4.017	4.132	4.087	0.045	Q
D03 91-34-0006 (PERKINS PLANT) 03-1E6704	2	5.139	5.169	5.154	0.021	Q
D03 91-58-0006 (HALLWOOD PLANT) 03-2C8601	37	4.625	5.583	5.06	0.242	Q
D03 91-39-0002 (VERNALIS) 03-3797U4	14	4.92	5.196	5.03	0.078	Q
D04 91-43-0004 (HANSON PERMANENTE CEMENT PERMANENTE QUARRY) 04-0120S4	24	4.33	5.583	4.965	0.32	M
D04 91-07-0004 (CLAYTON) 04-2285C4	8	4.351	5.029	4.675	0.219	MzV diabase
D04 91-01-0007 (SUNOL) 04-4470U4	13	4.22	4.98	4.537	0.216	QPc

Source Project EA	No. of Samples	Lowest Value	Highest Value	Ave με/°F	Standard Deviation	*Geologic Code
D06 91-15-0068 (GRIFFITH COMPANY) 06-0K8904 06-460604	10	3.713	4.533	4.187	0.359	Qoa
D06 91-15-0041 (SAN EMIDIO) 06-0L6404	6	3.943	4.287	4.131	0.112	Q
D06 91-10-0010 (CALMAT/SANGER) 06-324504	1	4.86	4.86	4.86	N/A	Qoa
D07 91-33-0008 (CABAZON QUARRY) 07-184104	2	4.441	4.671	4.556	0.163	Q
D07 91-19-0026 (HI-GRADE QUARRY) 07-199634	4	4.299	5.62	5.132	.575	Q
D08 91-36-0040 (LYTLE CREEK) 08-472224 12-0E5704	36	4.907	4.518	4.707	0.077	Q
D08 91-33-0072 (DILLON (AKA R-C SAND & GRAVEL)) 08-478604	16	3.84	4.17	4.001	0.082	Q
D08 91-36-0146 (MID-VALLEY SANITARY LANDFILL) 08-497504 12-0F0324	25	4.552	4.908	4.755	0.087	Q
D10 91-39-0014 (KERLINGER - HUCK) 10-0M8004	1	5.54	5.54	5.54	N/A	Q

Source Project EA	No. of Samples	Lowest Value	Highest Value	Ave µε/°F	Standard Deviation	*Geologic Code
D10 91-05-0006 (ROBIE RANCH) 10-0G4704	8	4.811	5.403	5.169	0.190	Qpc
D11 91-13-0011 (NILAND SITE (FRINK)) 11-167894	50	3.605	4.239	3.88	0.149	Q
D11 91-37-0035 (OTAY RANCH PIT #11) 11-265304	1	4.587	4.587	4.587	N/A	Qoa
D12 91-36-0006 (FOOTHILL QUARRY AND PLANT) 12-071624	37	4.351	4.917	4.616	0.129	Q
D12 91-36-0014 (UPLAND) 12-071634	10	4.303	4.534	4.42	0.065	Q

*Geologic Code:
Kjf - Franciscan Complex: Cretaceous and Jurassic sandstone with smaller amounts of shale, chert, limestone, and conglomerate. Includes Franciscan melange, except where separated.
Q - Alluvium, lake, playa, and terrace deposits; unconsolidated and semi-consolidated. Mostly nonmarine, but includes marine deposits near the coast.
M - Sandstone, shale, siltstone, conglomerate, and breccia; moderately to well consolidated.
MzV - Undivided Mesozoic volcanic and metavolcanic rocks. Andesite and rhyolite flow rocks, greenstone, volcanic breccia and other pyroclastic rocks; in part strongly metamorphosed. Includes volcanic rocks of Franciscan Complex: basaltic pillow lava, diabase, greenstone, and minor pyroclastic rocks.
QPc - Pliocene and/or Pleistocene sandstone, shale, and gravel deposits; mostly loosely consolidated.
Qoa - Older alluvium, lake, playa, and terrace deposits

Table 2 Summary by District

District No. of Projects	No. of Samples	Lowest Value	Highest Value	Average	Std Dev
D01 - 1	2	5.167	5.389	5.278	0.157
D02 - 1	5	4.017	4.132	4.087	0.045
D03 - 3	53	4.625	5.583	5.055	0.207
D04 - 3	45	4.22	5.583	4.79	0.335
D06 - 4	17	3.713	4.86	4.207	0.325
D07 - 2	6	4.299	5.61	4.94	0.540
D08 - 3	63	3.84	4.908	4.528	0.319
D10 - 2	9	4.811	5.54	5.21	0.217
D11 - 2	51	3.605	4.587	3.894	0.178
D12 - 4	61	4.303	4.917	4.624	0.161
Overall results	312	3.605	5.61	4.578	0.465

Table 3 Summary by Project

Project Aggregate Source	No. of Samples	Lowest Value	Highest Value	Average	Std Dev	Testing Lab
01-480504 91-23-0015 (HARRIS QUARRY)	2	5.167	5.389	5.278	0.157	AMEC
D02 91-47-0016 (UPTON MINE) 02-3E7604	5	4.017	4.132	4.087	0.045	RMA Group
03-1E6704 91-34-0006 (PERKINS PLANT)	2	5.139	5.169	5.154	0.021	Twining
03-2C8601 91-58-0006 (HALLWOOD PLANT)	37	4.625	5.583	5.06	0.242	Twining
03-3797U4 91-39-0002 (VERNALIS)	14	4.92	5.196	5.030	0.078	RMA Group
04-0120S4 91-43-0004(HANSON PERMANENTE CEMENT PERMANENTE QUARRY)	20	4.873	5.583	5.080	0.202	Twining
04-0120S4 91-43-0004(HANSON PERMANENTE CEMENT PERMANENTE QUARRY)	4	4.33	4.435	4.392	0.050	Translab
04-2285C4 91-07-0004 (CLAYTON)	8	4.351	5.029	4.675	0.218	Twining

Project Aggregate Source	No. of Samples	Lowest Value	Highest Value	Average	Std Dev	Testing Lab
04-4470U4 **91-01-0007 (SUNOL)**	13	4.22	4.98	4.537	0.215	RMA Group
06-0K8904 **91-15-0068 (GRIFFITH COMPANY)**	4	3.713	3.82	3.775	0.054	Translab
06-0L6404 **91-15-0041 (SAN EMIDIO)**	6	3.943	4.287	4.131	0.112	Translab
06-324504 **91-10-0010 (CALMAT/SANGER)**	1	4.86	4.86	4.86	N/A	RMA Group
06-460604 **91-15-0068 (GRIFFITH COMPANY)**	6	4.34	4.533	4.461	0.068	RMA Group
07-184104 **91-33-0008 (CABAZON QUARRY)**	2	4.441	4.671	4.556	0.163	Twining
07-199634 **91-19-0026 (HI-GRADE QUARRY)**	**4**	4.299	5.62	5.132	.575	Twining
08-472224 **91-36-0040 (LYTLE CREEK)**	33	4.518	4.843	4.691	0.058	RMA Group
08-478604 **91-33-0072 (DILLON (AKA R-C SAND & GRAVEL))**	16	3.84	4.17	4.001	0.082	Translab
08-497504 **91-36-0146 (MID-VALLEY SANITARY LANDFILL)**	14	4.552	4.908	4.745	0.092	RMA Group
10-0M8004 **91-39-0014 (KERLINGER - HUCK)**	1	5.54	5.54	5.54	N/A	CEMEX
10-0G4704 **91-05-0006 (ROBIE RANCH)**	8	4.811	5.403	5.169	0.190	Twining
11-167894 **91-13-0011 (NILAND SITE (FRINK))**	50	3.605	4.239	3.88	0.149	Translab
11-265304 **91-37-0035 (OTAY RANCH PIT #11)**	1	4.587	4.587	4.587	N/A	RMA Group
12-0E5704 **91-36-0040 (LYTLE CREEK)**	3	4.832	4.907	4.878	0.04	RMA Group

Project Aggregate Source	No. of Samples	Lowest Value	Highest Value	Average	Std Dev	Testing Lab
12-071624 91-36-0006 (FOOTHILL QUARRY AND PLANT)	37	4.351	4.917	4.616	0.129	Twining
12-071634 91-36-0014 (UPLAND)	10	4.303	4.534	4.42	0.065	Leighton
12-0F0324 91-36-0146 (MID-VALLEY SANITARY LANDFILL)	11	4.634	4.885	4.768	0.083	RMA Group

Coefficient of Thermal Expansion Testing Laboratories

Caltrans-DES METS TRANSLAB, MS 5
5900 Folsom Blvd, Sacramento, CA 95819-4612

Twining
2883 East Spring Street Suite 300, Long Beach, CA 90806

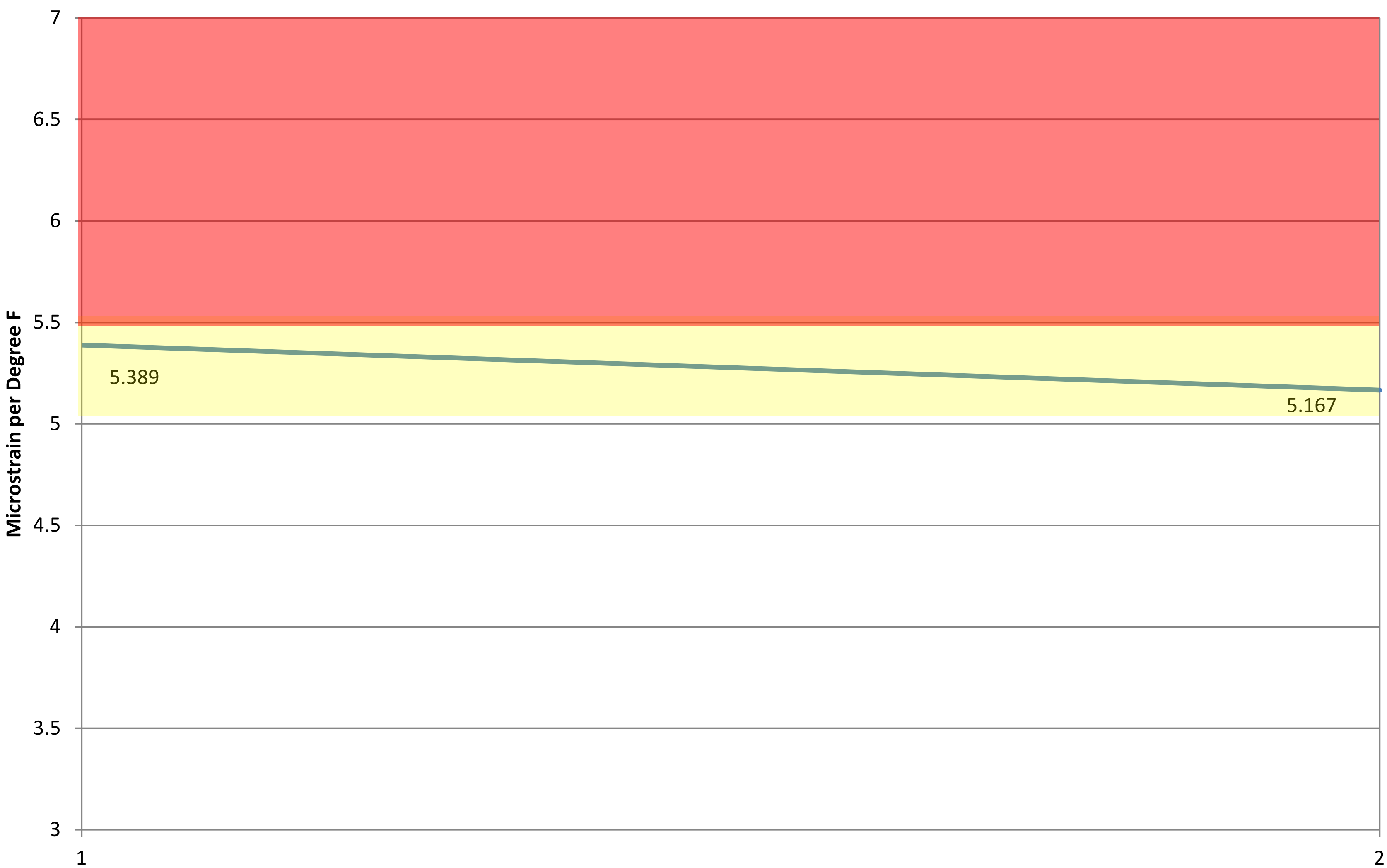
RMA Group
3150 Fitzgerald Road, Rancho Cordova, CA 95742

Leighton Consulting Inc. (Smith-Emery Lab)
17781 Cowan, Irvine, CA 92614

AMEC
9177 Sky Park Court, San Diego, CA 92123

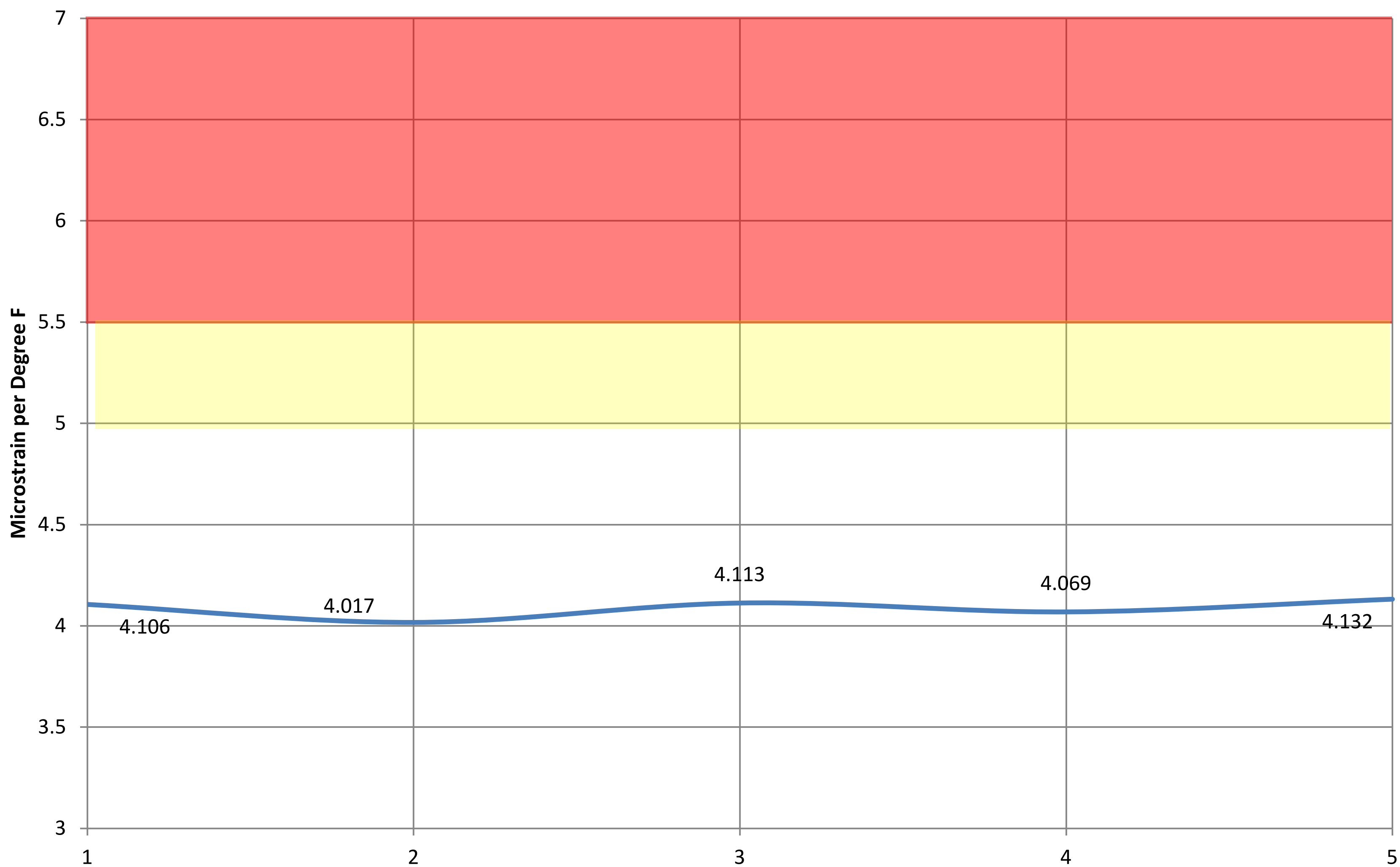
CEMEX Tampa Technical Center
6725 78th Street, Riverview, FL 33578

Figure 1: Coefficient of Thermal Expansion Results for Harris Quarry SMARA 91-23-0015
Project EA 01-480504



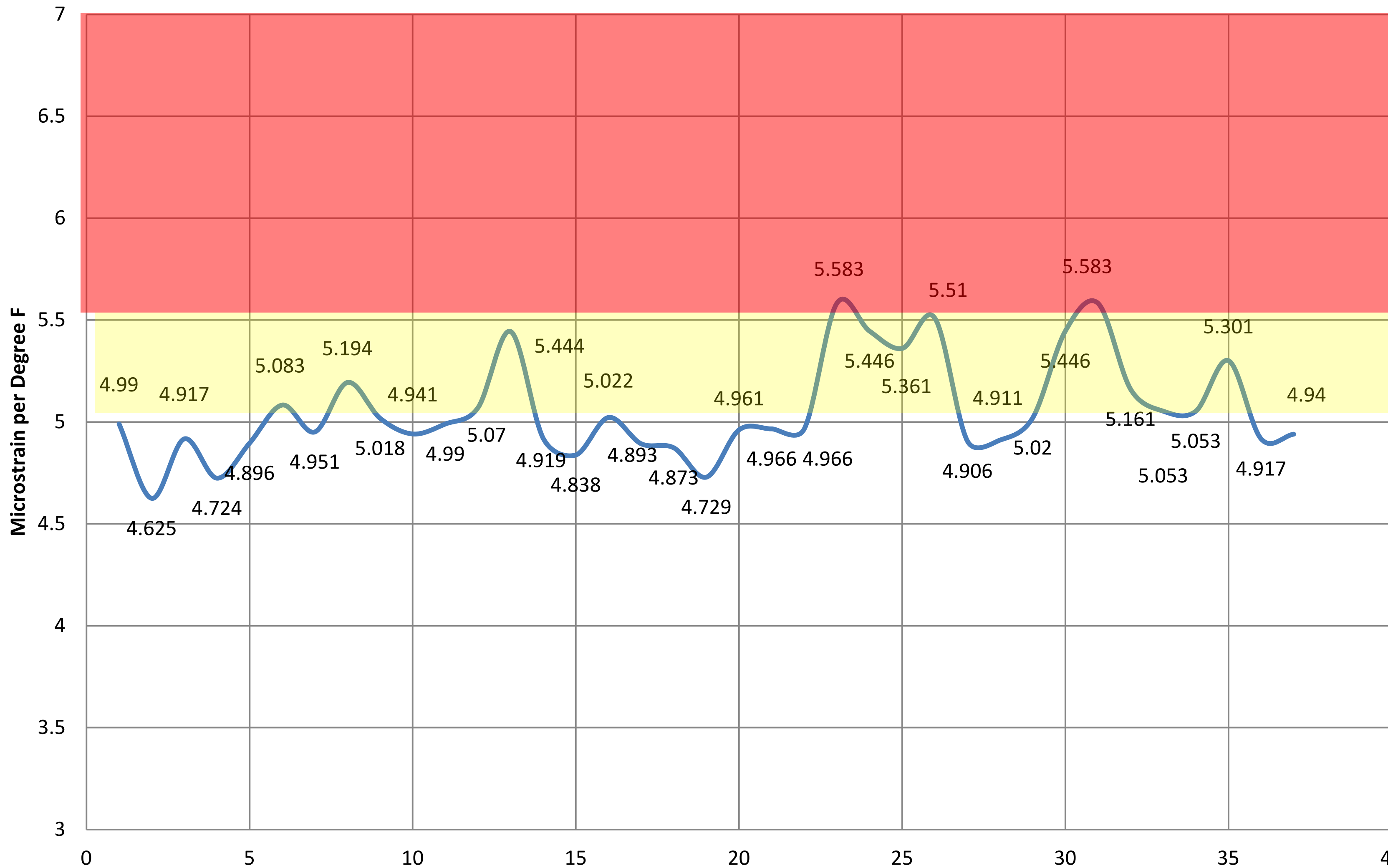
Testing performed by Amec. Average from 2 test results is 5.278 with a standard deviation of 0.157

Figure 2: Coefficient of Thermal Expansion Results for Upton Quarry SMARA 91-47-0016
Project EA 02-3E7604



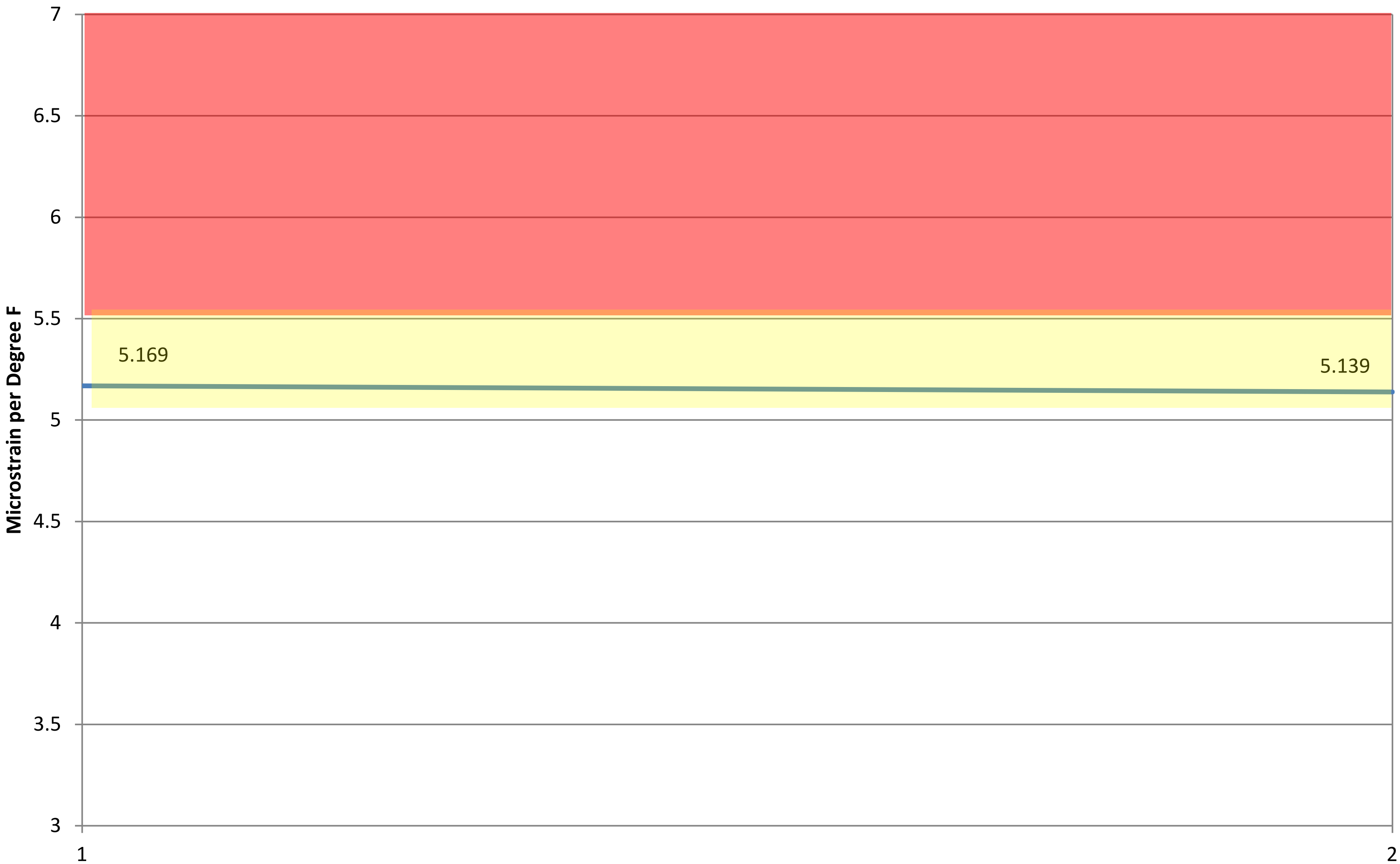
Testing performed by RMA Group. Average from 5 test results is 4.087 with a standard deviation of 0.046

Figure 3: Coefficient of Thermal Expansion for Hallwood Quarry SMARA 91-58-0006
Project EA 03-2C8601



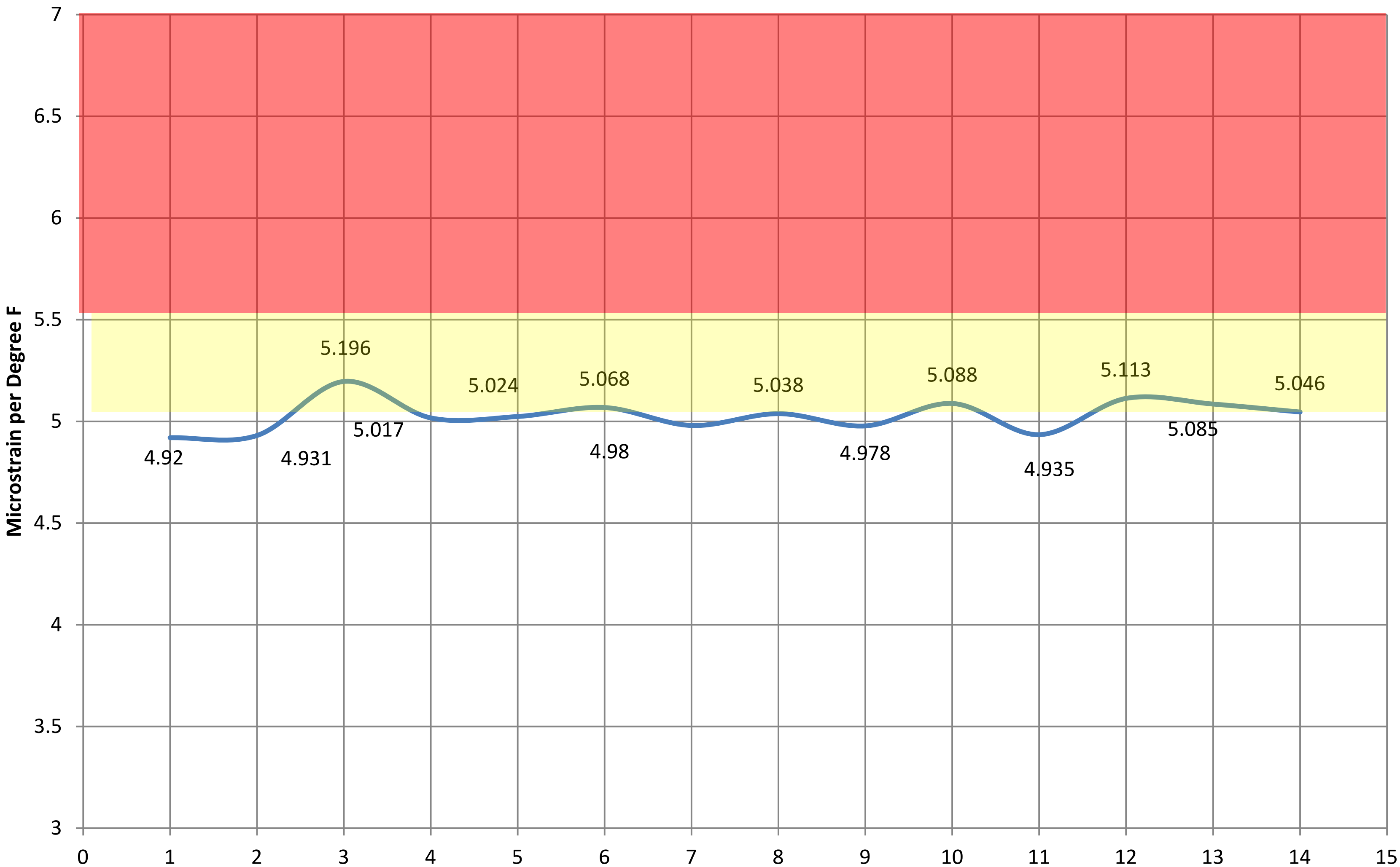
Testing performed by Twining. Average from 37 test results is 5.06 with a standard deviation of 0.242

Figure 4: Coefficient of Thermal Expansion Results for Perkins Quarry SMARA 91-34-0006
Project EA 03-1E6704



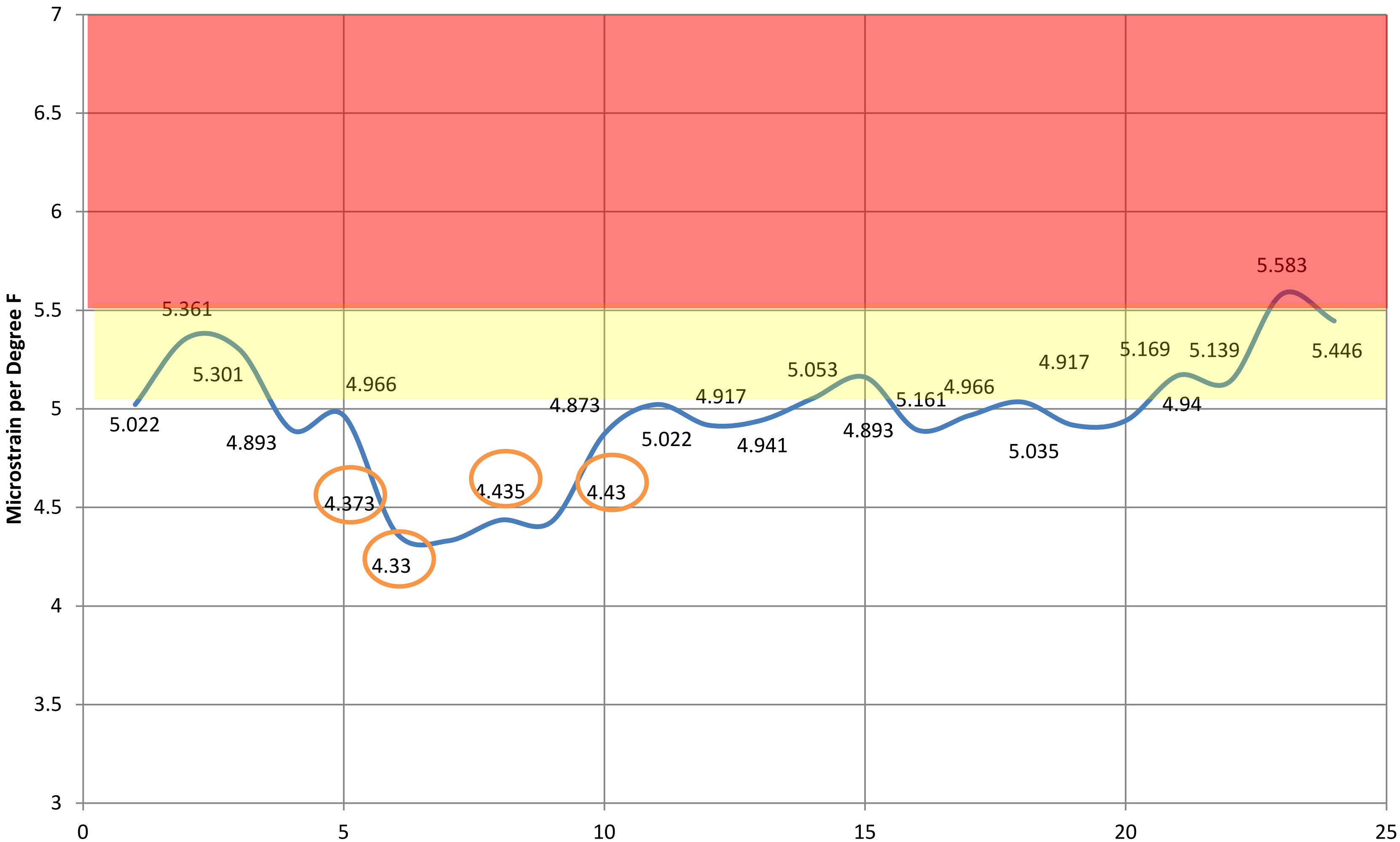
Testing performed by Twining. Average from 2 test results is 5.154 with a standard deviation of 0.021

Figure 5: Coefficient of Thermal Expansion Results for Vernalis Quarry SMARA 91-39-0002
Project EA 03-3797U4



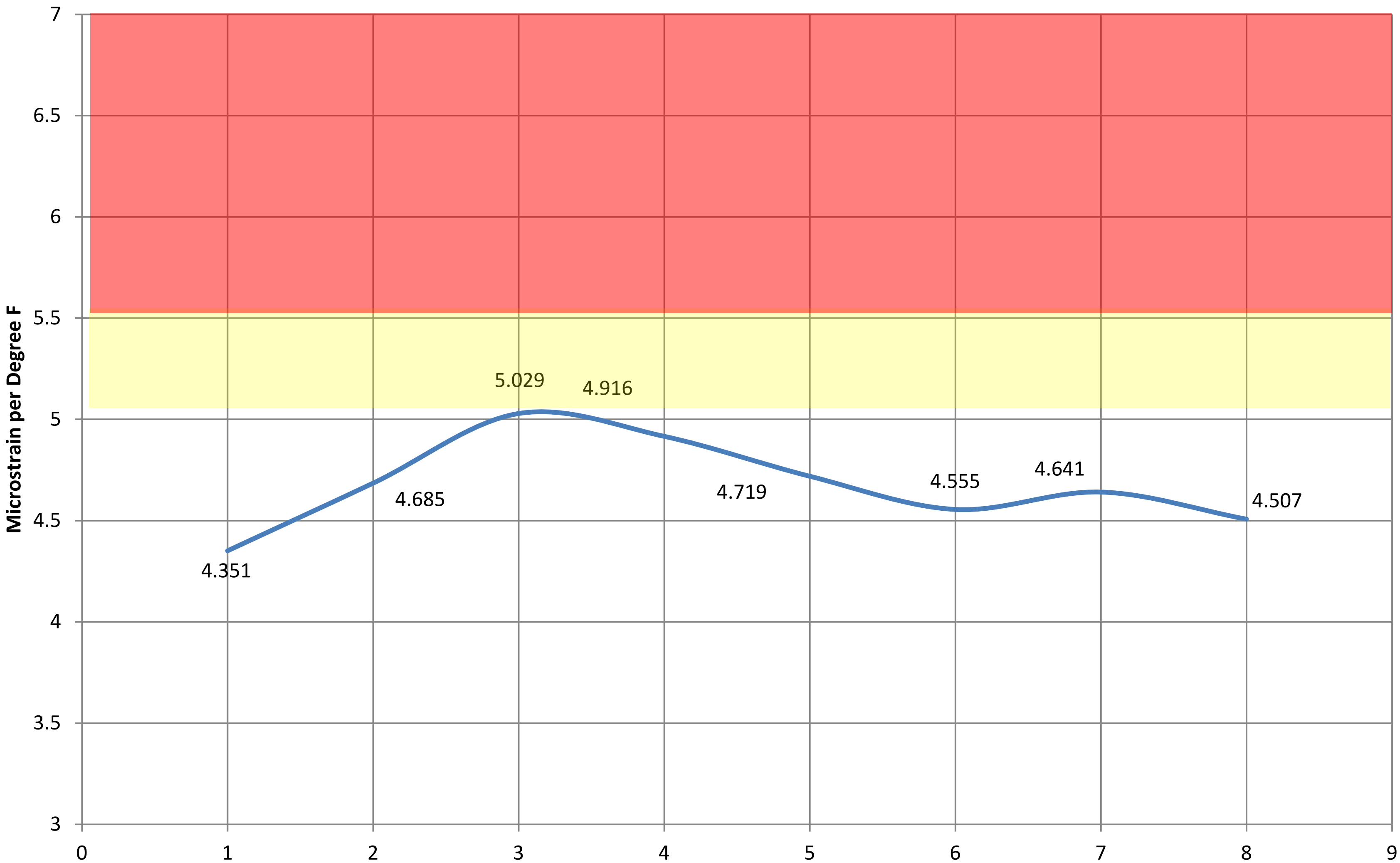
Testing performed by RMA Group. Average from 14 test results is 5.03 with a standard deviation of 0.078

Figure 6: Coefficient of Thermal Expansion Results for Hanson Quarry SMARA 91-43-0004
Project EA 04-0120S4



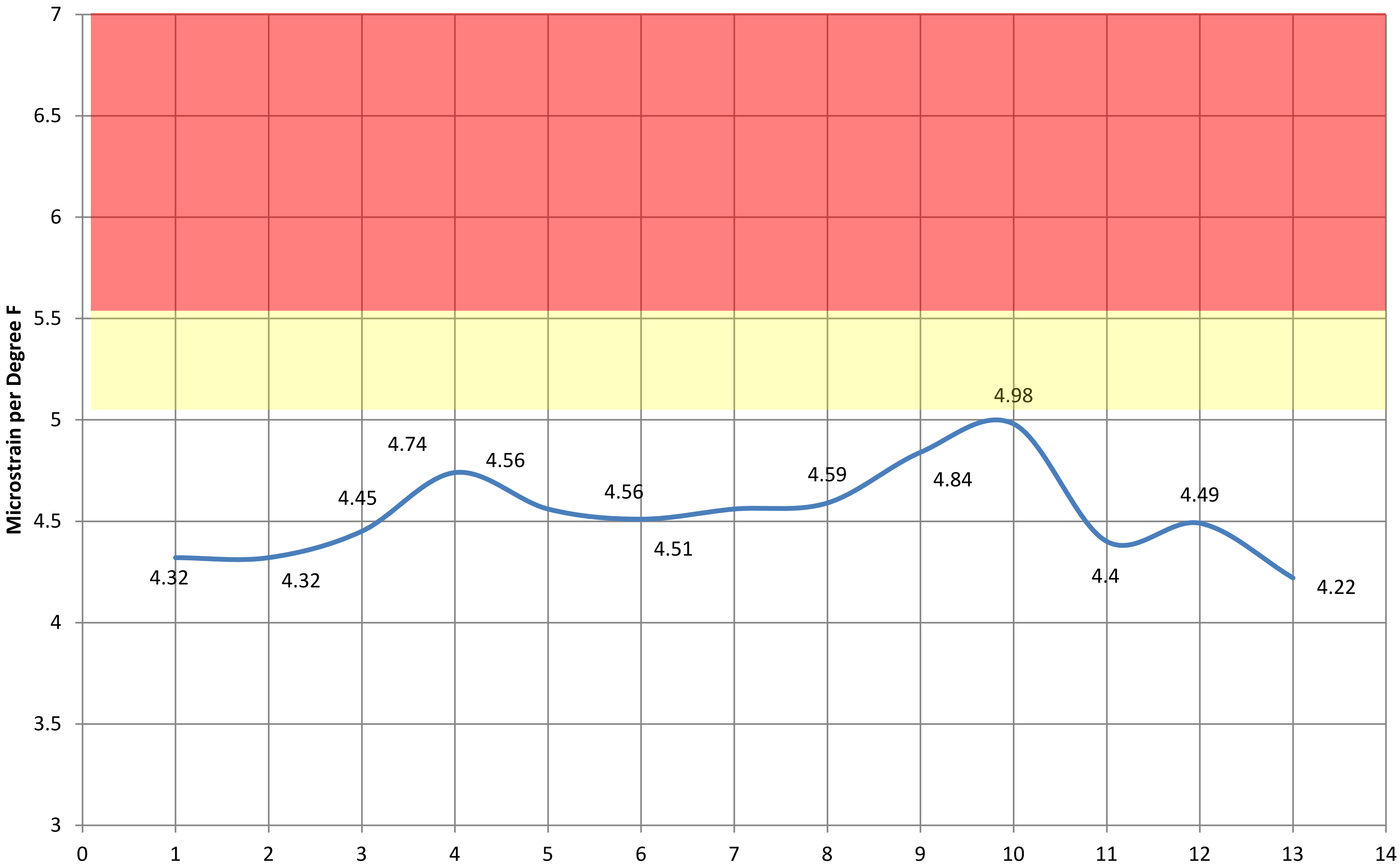
Testing performed by Twining and Translab. Average from 24 test results is 4.965 with a standard deviation of 0.32

Figure 7: Coefficient of Thermal Expansion Results for Clayton Quarry SMARA 91-07-0004
Project EA 04-2285C4



Testing performed by Twining. Average from 8 test results is 4.675 with a standard deviation of 0.218

Figure 8: Coefficient of Thermal Expansion Results for Sunol Quarry SMARA 91-01-0007
Project EA 04-4470U4



Testing performed by RMA Group. Average from 13 test results is 4.537 with a standard deviation of 0.215

Figure 9: Coefficient of Thermal Expansion Result for Kerlinger-Huck Quarry SMARA 91-39-0014
Project EA 10-0M8004

Testing performed by CEMEX. 1 test result with a value of 5.54

Figure 10: Coefficient of Thermal Expansion Result for Calmat/Sanger Quarry SMARA 91-10-0010
Project EA 06-324504

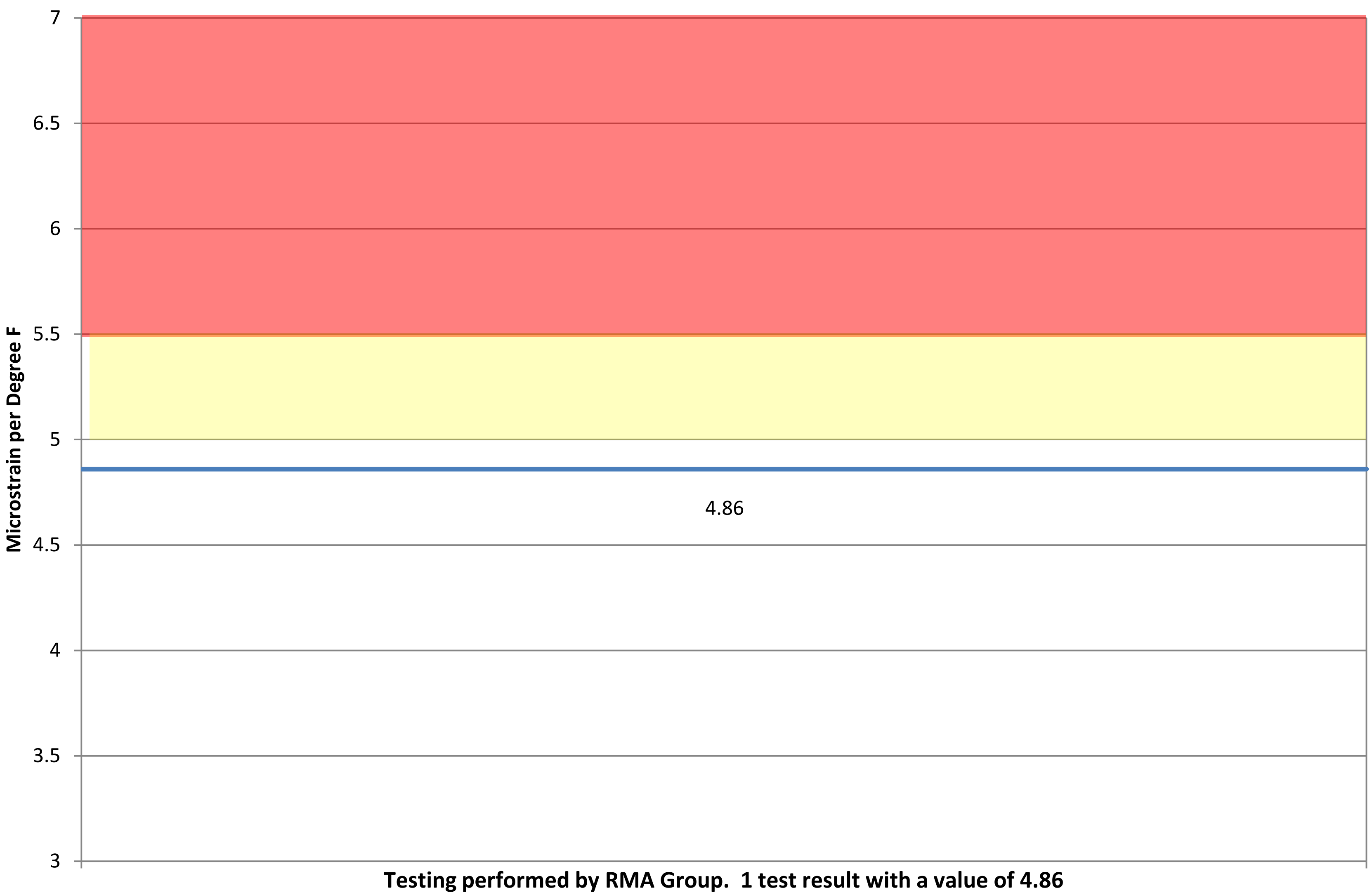


Figure 11: Coefficient of Thermal Expansion Results for Griffith Quarry SMARA 91-15-0068 Project EA 06-0K8904 and 06-460604

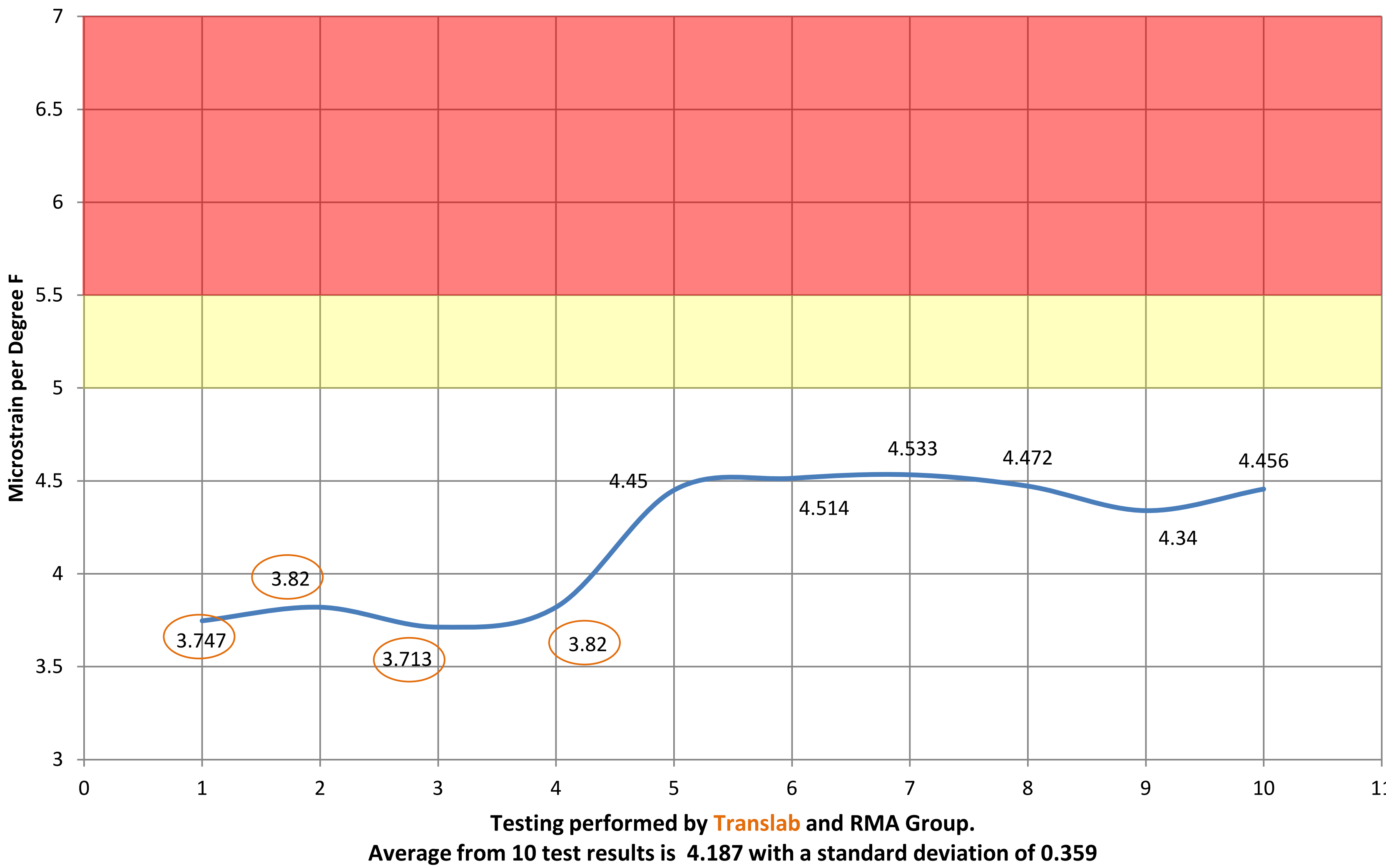
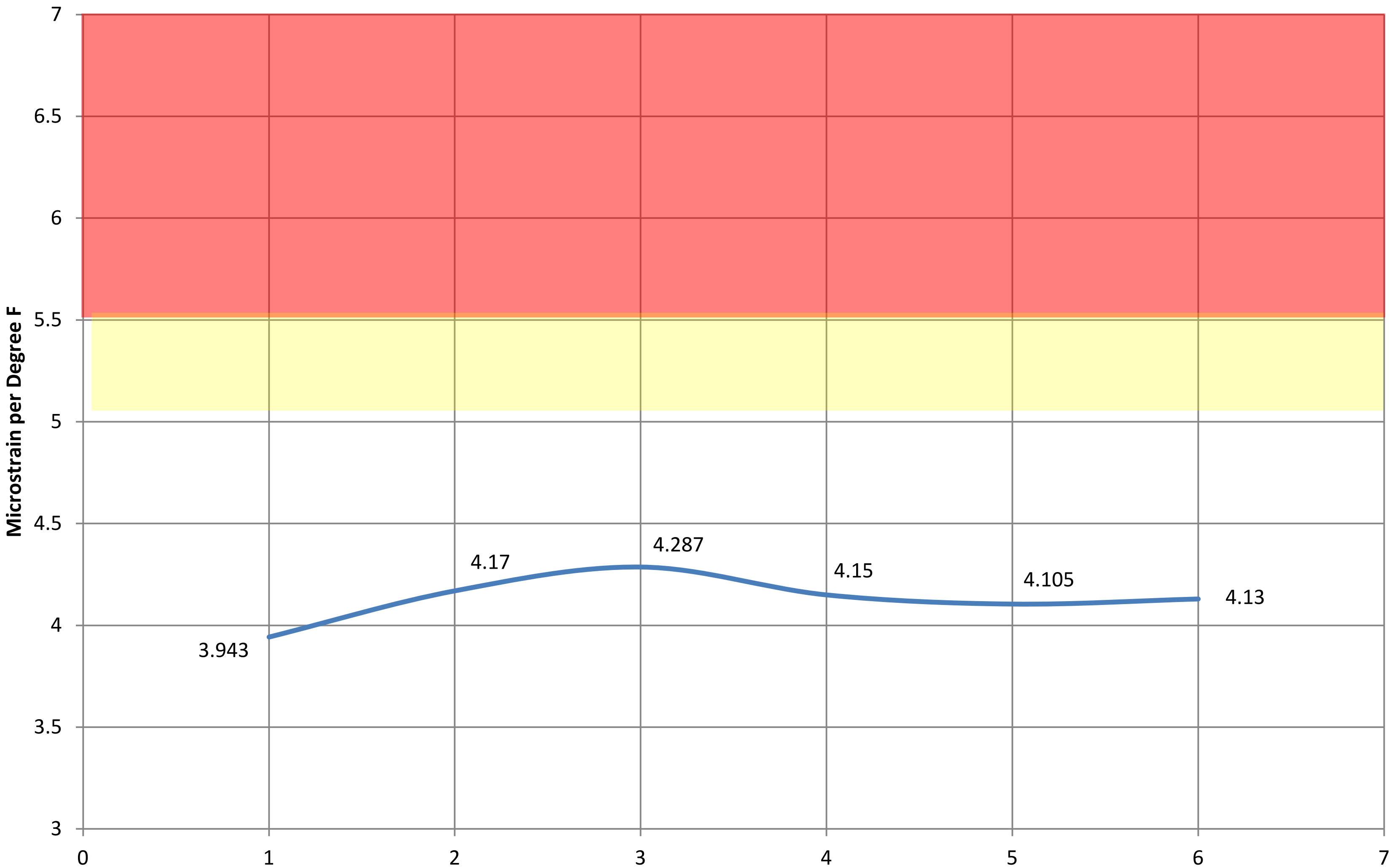
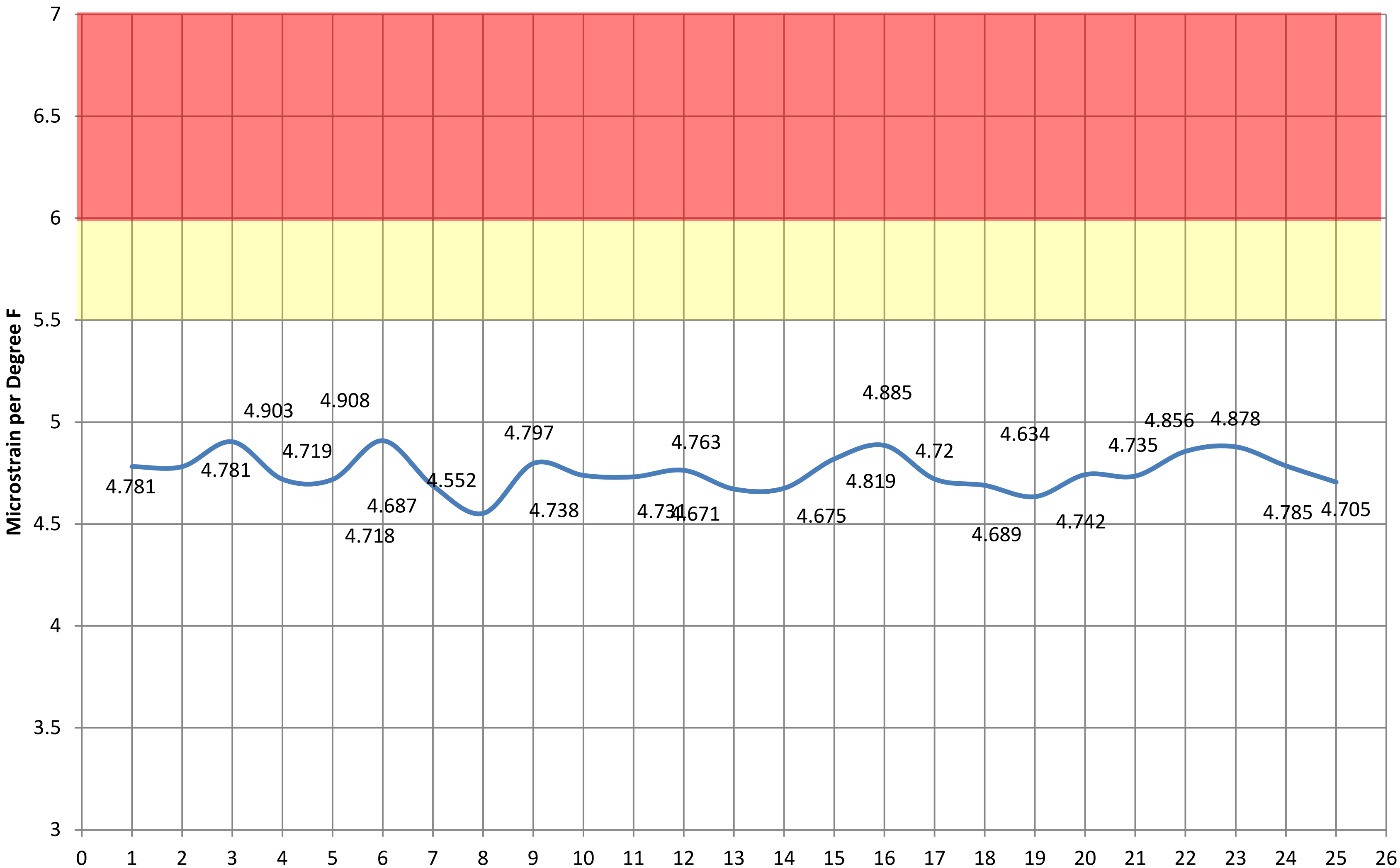


Figure 12: Coefficient of Thermal Expansion Results for San Emidio SMARA 91-15-0041 Project EA 06-0L6404



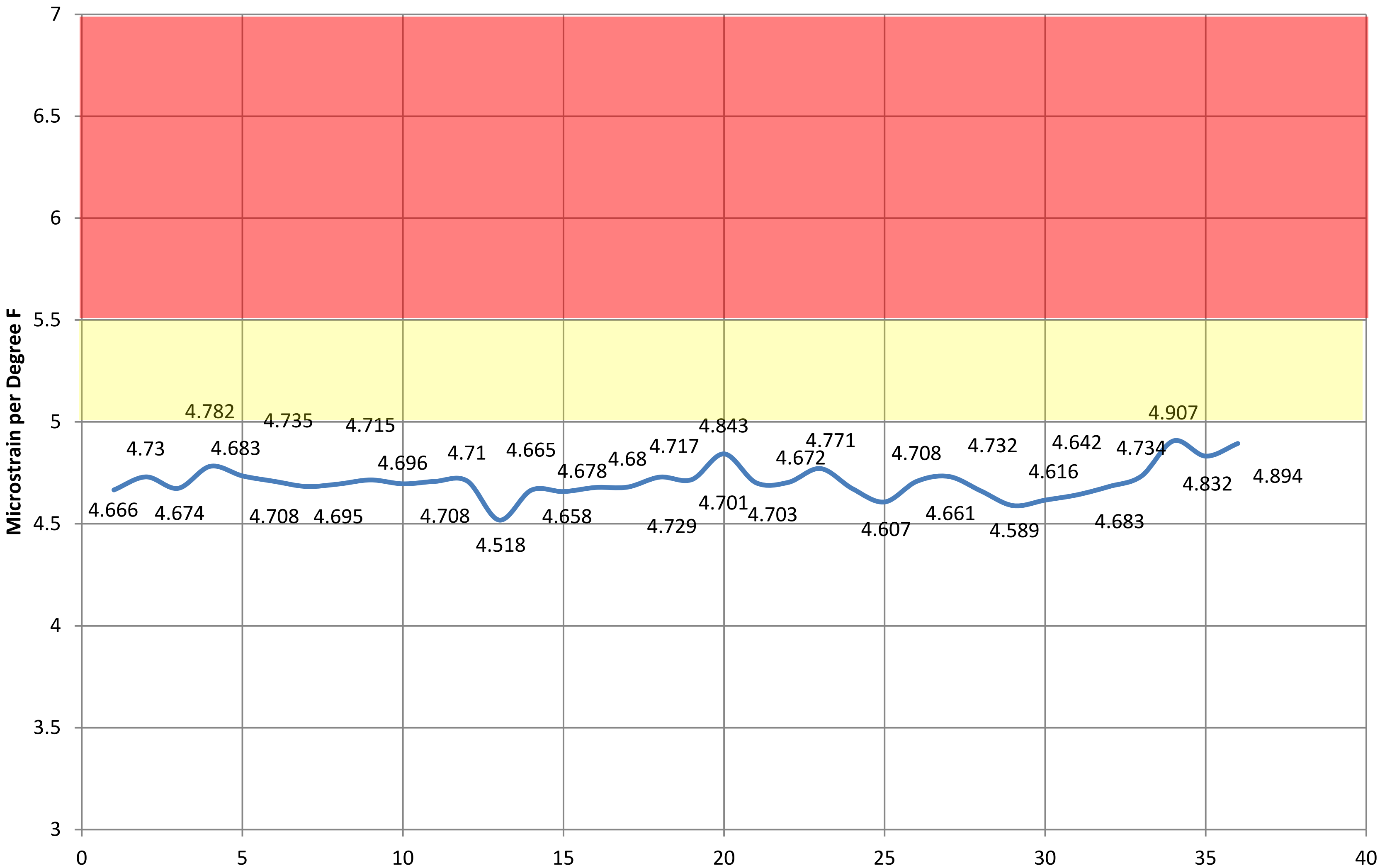
Testing performed by Translab. Average from 6 test results is 4.131 with a standard deviation of 0.112

Coefficient of Thermal Expansion Results for Mid-Valley Quarry SMARA 91-36-0146
Project EA 08-497504 and 12-0F0324 (last eleven results)



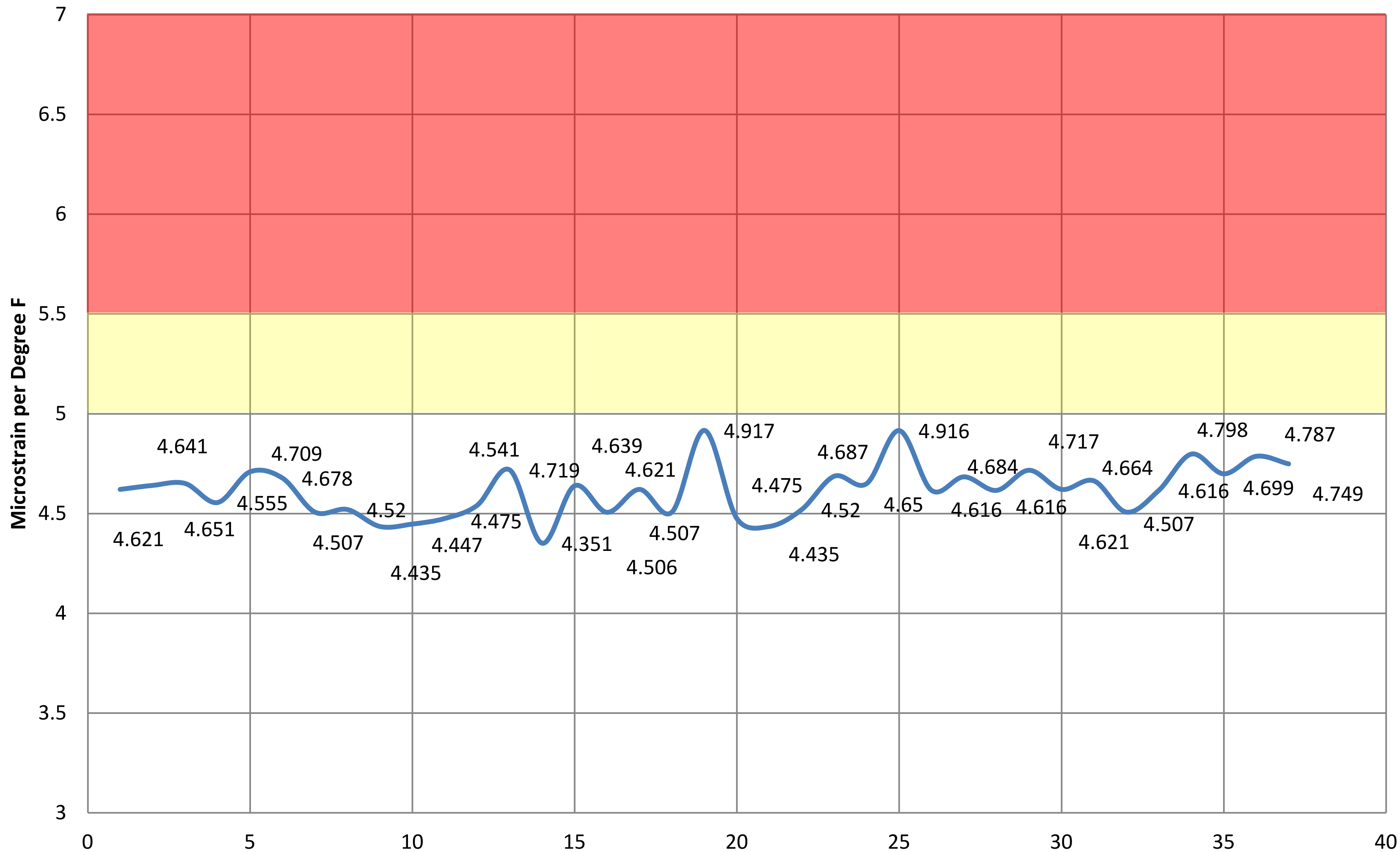
Testing performed by RMA Group. Average from 25 test results is 4.755 with a standard deviation of 0.087

Figure 14: Coefficient of Thermal Expansion Results for Lytle Creek Quarry SMARA 91-36-0040 Project EA 08-472224 and 12-05704 (last three results)



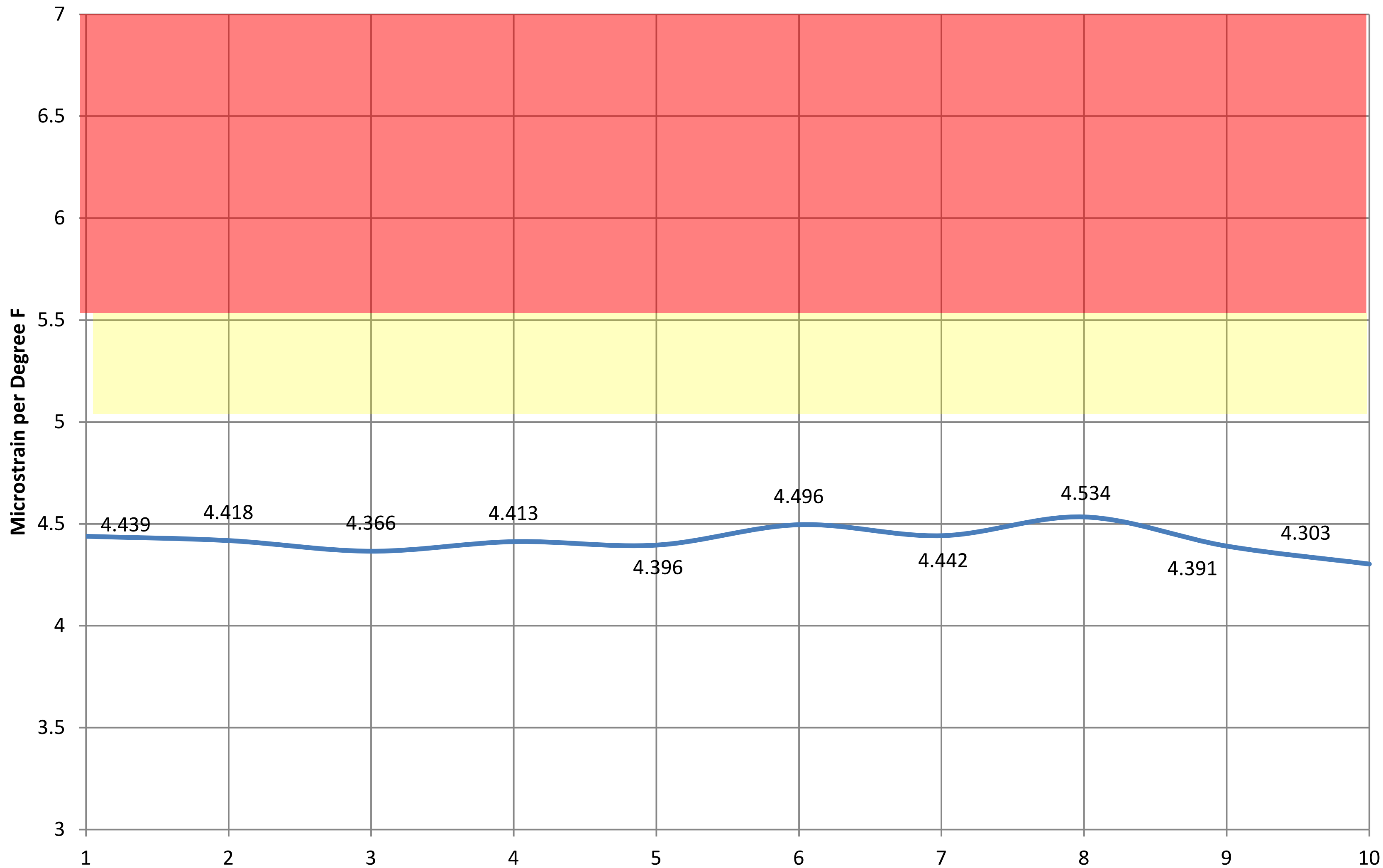
Testing performed by RMA Group. Average from 36 test results is 4.707 with a standard deviation of 0.077

Figure 15: Coefficient of Thermal Expansion Results for Foothill Quarry SMARA 91-36-0006
Project EA 12-071624



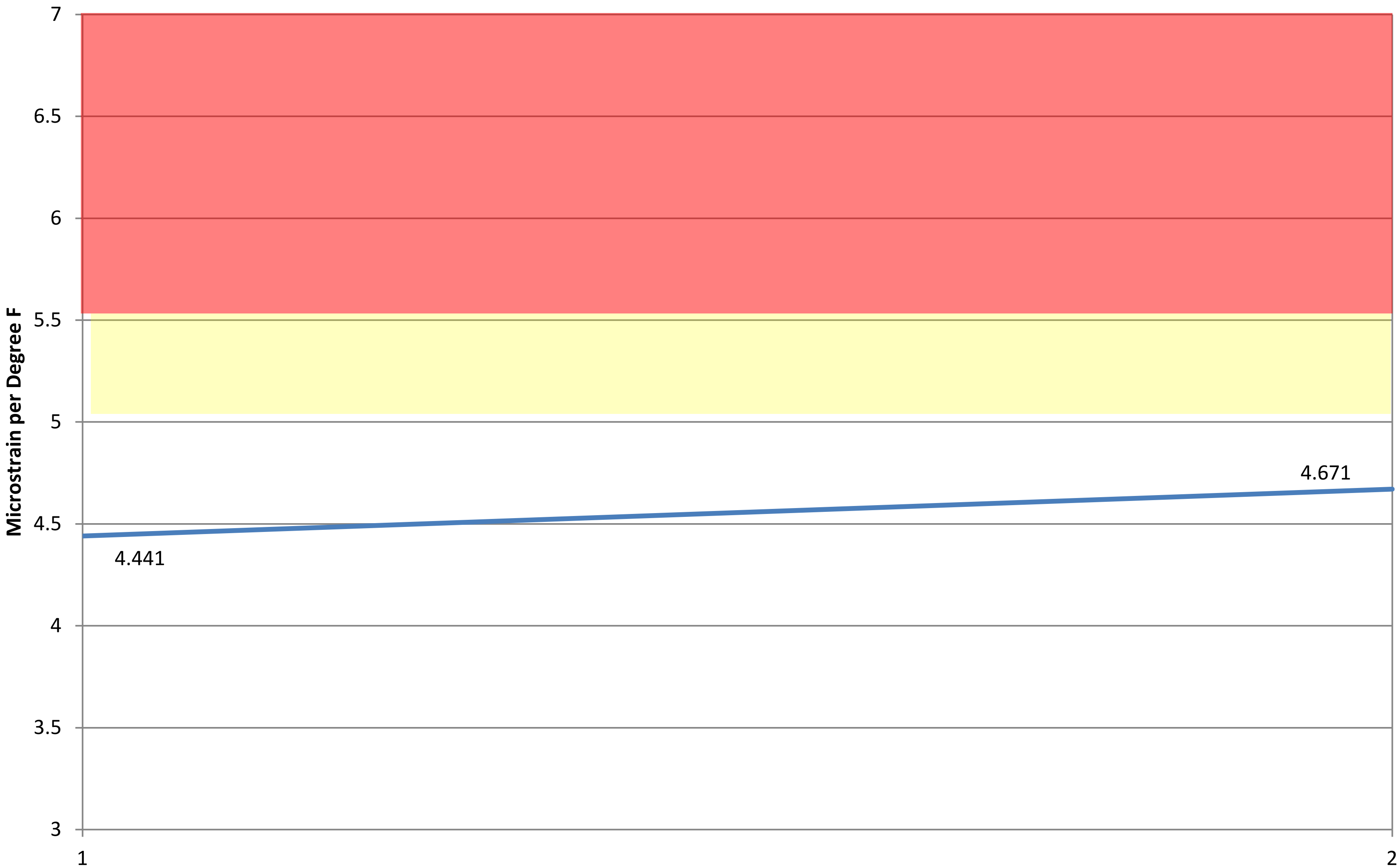
Testing performed by Twining. Average from 37 test results is 4.616 with a standard deviation of 0.129

Figure 16: Coefficient of Thermal Expansion Results for Upland Quarry SMARA 91-36-0014
Project EA 12-071634



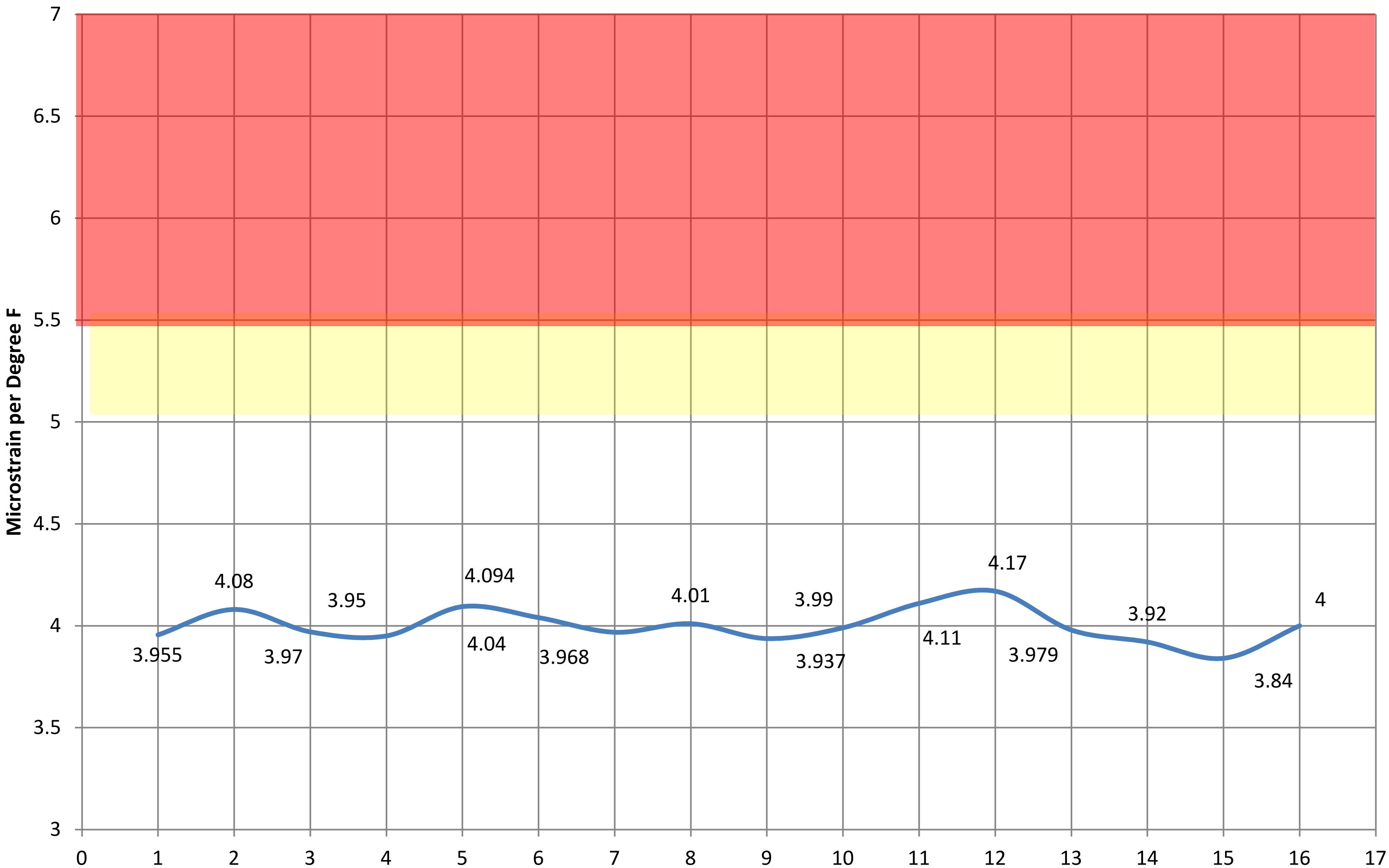
Testing performed by Leighton. Average from 10 test results is 4.42 with a standard deviation of 0.065

Figure 17: Coefficient of Thermal Expansion Results for Cabazon Quarry SMARA 91-33-0008
Project EA 07-184104



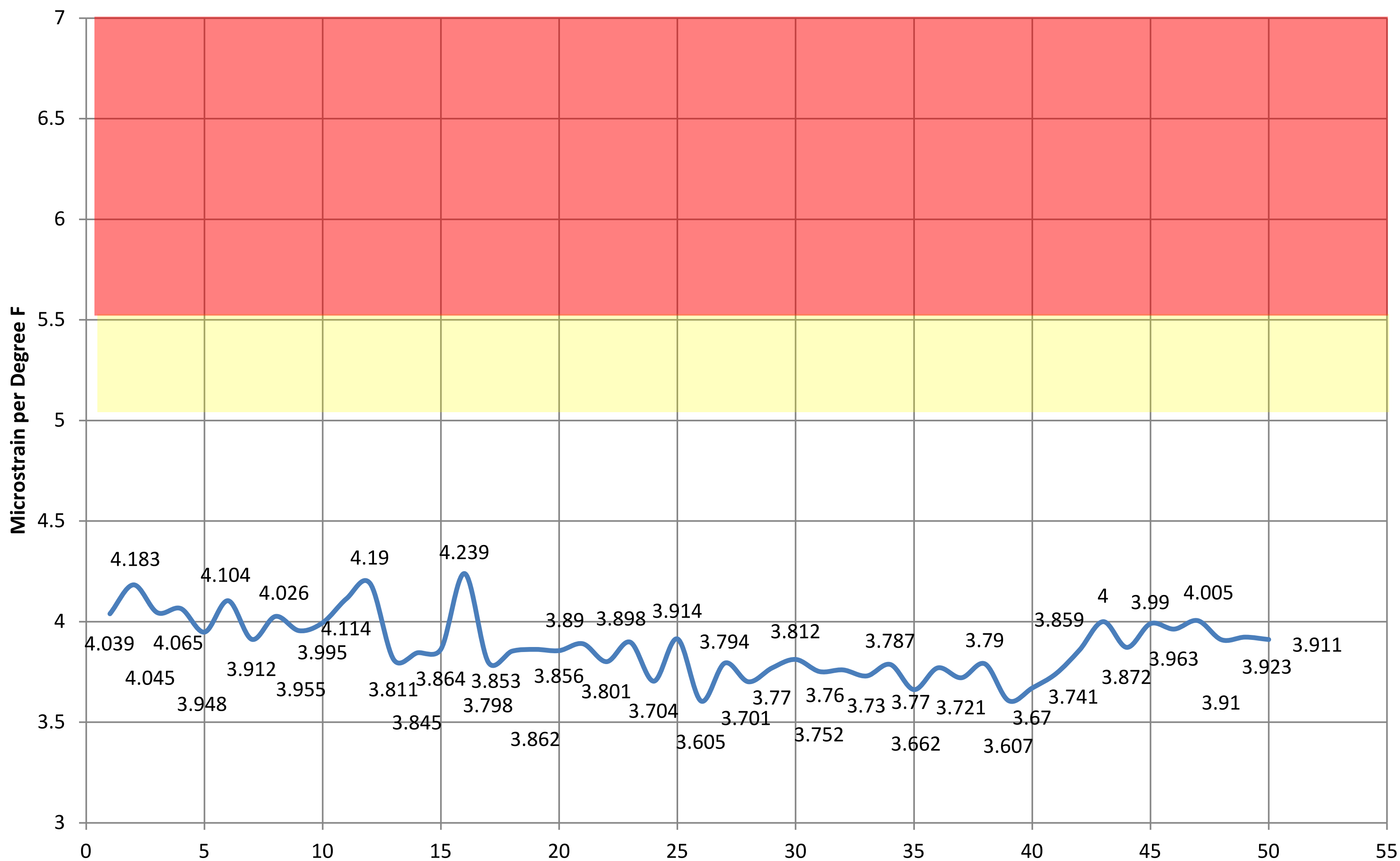
Testing performed by Twining. Average from 2 test results is 4.556 with a standard deviation of 0.163

Figure 18: Coefficient of Thermal Expansion Results for Dillon Quarry SMARA 91-33-0072
Project EA 08-478604



Testing performed by Translab. Average from 16 test results is 4.001 with a standard deviation of 0.082

Figure 19: Coefficient of Thermal Expansion Results for Niland Site (Frink) Quarry SMARA 91-13-0011
Project EA 11-167894

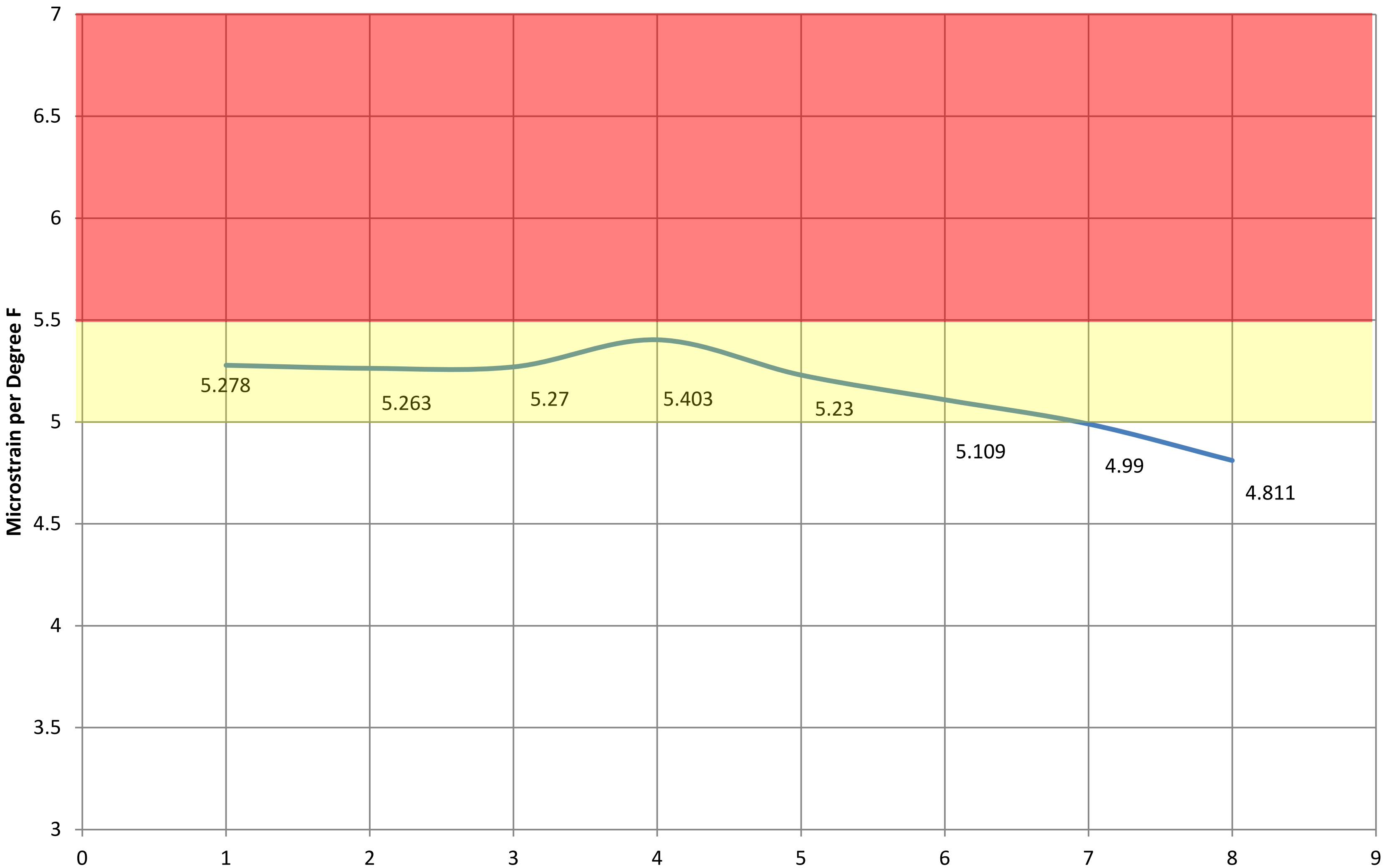


Testing performed by Translab. Average from 50 test results is 3.88 with a standard deviation of 0.149

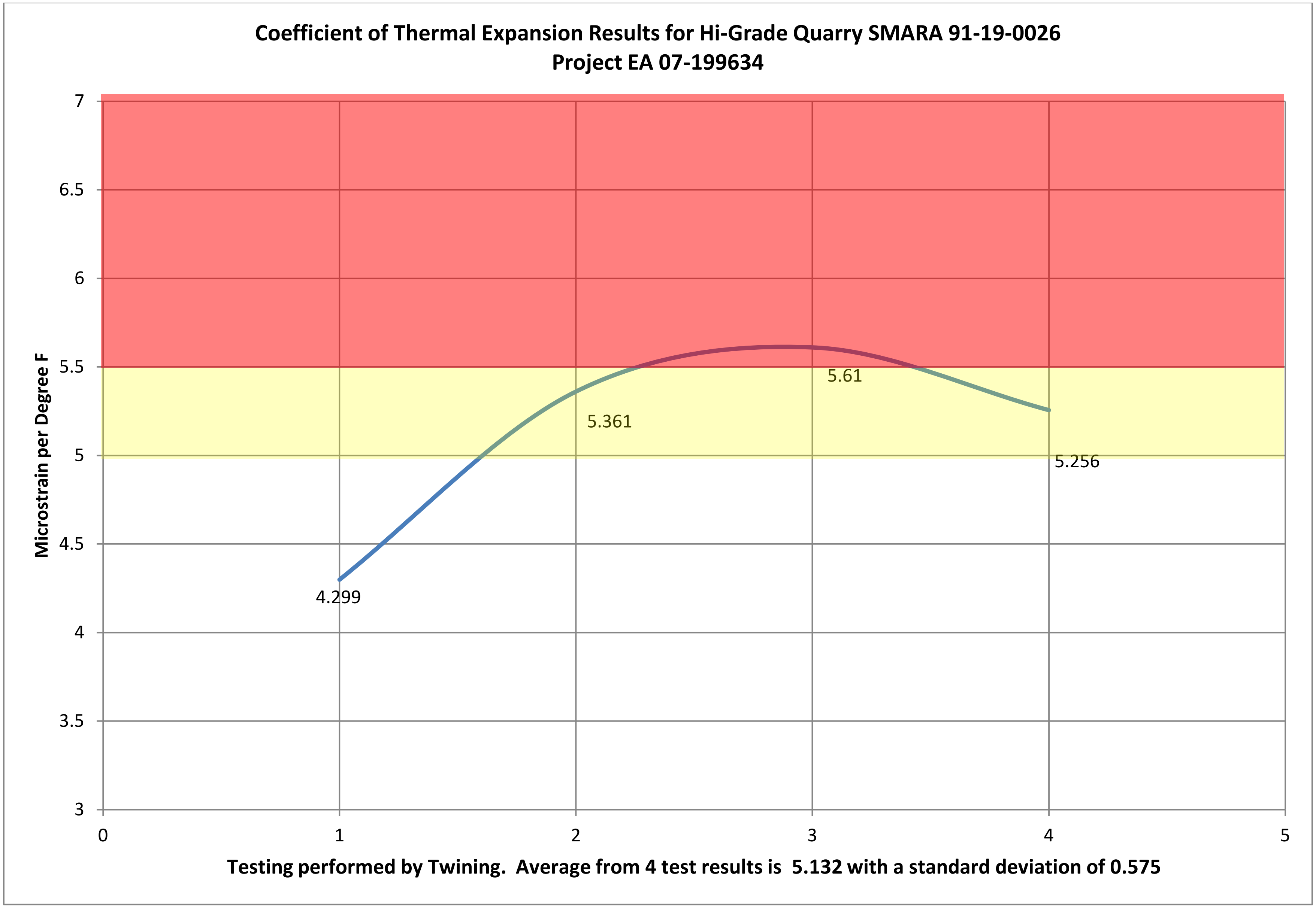
Figure 20: Coefficient of Thermal Expansion Result for Otay Ranch Quarry SMARA 91-37-0035
Project EA 11-265304

Testing performed by RMA Group. 1 test result with a value of 4.587

Figure 21: Coefficient of Thermal Expansion Results for Robie Ranch Quarry SMARA 91-06-0006
Project EA 10-0G4704



Testing performed by Twining. Average from 8 test results is 5.169 with a standard deviation of 0.190


Coefficient of Thermal Expansion Results for Hi-Grade Quarry SMARA 91-19-0026
Project EA 07-199634
Microstrain per Degree F
7
6.5
6
5.5
5
4.5
4
3.5
3
0
1
2
3
4
5
4.299
5.361
5.61
5.256
Testing performed by Twining. Average from 4 test results is 5.132 with a standard deviation of 0.575

TWINING

Corporate Headquarters 2883 East Spring Street, Suite 300, Long Beach, CA 90806
Laboratory 3310 Airport Way, Long Beach, CA 90806
Phone 562.426.3355 / **Fax** 562.426.6424 / **Web** twininginc.com

CLIENT: Peterson Chase

DATE: August 1, 2012
Project #: 120219.1
Lab #: CH12-0285

COEFFICIENT OF THERMAL EXPANSION REPORT

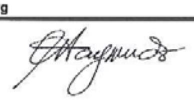
MIXTURE PROPORTIONS:

Mix: 3.5 Mpa -650 Flex
Cement ---
Fly Ash ---
GGBFS NA
1" Rock ---
3/8" Rock ---
WCS ---

Date Tested: July 4, 2012
Specimen Type: Concrete Cylinder
Description: 4" X 8" Cylinder
Source: Twining Long Beach

Project:	CT 07-184104 Rte 5 @ 105/101 Separation	
Laboratory:	Twining	
Technician:	R. Davenport	
Comment:	28 days	

		3.5 Mpa- 650 Flex	
Specimen Identification		**CH12-0285**	
Specimen Diameter	mm	4.00	
Specimen L_0	mm	178.85	
Frame S/N		133725	
Frame Cf	mm/mm/°C	20.158E-6	
FCS Serial No.		102801G	
FCS CTE	mm/mm/°C	10.400E-6	
T1	°C	49.45	
T2	°C	10.41	
T3	°C	49.39	
$\Delta T_1 = T_2 - T_1$	°C	-39.04	
$\Delta T_2 = T_3 - T_1$	°C	38.98	
L_1	mm	-0.11610	
L_2	mm	-0.03361	
L_3	mm	-0.11507	
$\Delta L_{m1} = L_2 - L_1$	mm	0.08249	
$\Delta L_{m2} = L_3 - L_2$	mm	-0.08146	
$\Delta L_{f1} = Cf^*L_0^*\Delta T_1$	mm	-0.14075	
$\Delta L_{f2} = Cf^*L_0^*\Delta T_2$	mm	0.14053	
$\Delta L_{a1} = \Delta L_{m1} + \Delta L_{f1}$	mm	-0.05826	
$\Delta L_{a2} = \Delta L_{m2} + \Delta L_{f2}$	mm	0.05907	
$CTE_1 = \Delta L_{a1}/L_0/\Delta T_1$	mm/mm/°C	8.344E-6	
$CTE_2 = \Delta L_{a2}/L_0/\Delta T_2$	mm/mm/°C	8.473E-6	
CTE_{avg}	mm/mm/°C	**8.409E-6**	
CTE_{avg}	in/in/F	**4.671E-6**	



Eugene Raymundo
Project Engineer, Applied Engineering & Research

T:\Projects\2012 TLSC Projects\120219.1 - CT 07-184104 Rte 5 Separation\CTE\6-4-12


Upton 4.087
2
1
Harris 5.278
Hallwood 5.06
3
Perkins 5.154
Robie Ranch 5.169
Clayton 4.675
Kerlinger Huck 5.54
Vernalis 5.03
Sunol 4.537
Hanson 4.965
Sanger 4.86
9
6
5
Griffith 4.187
San Emidio 4.131
8
Hi-Grade 5.132
Upland 4.42
Foothill 4.616
Cabazon 4.556
Dillon 4.001
12
Nilan
11
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Mechanistic-Empirical (M-E) Design Results

Mechanistic-Empirical (M-E) Design methodology is based on software-generated pavement responses (stresses, strains, and deflections) computed using detailed traffic loading, material properties, and environmental data. The responses are used to compute incremental damage over time. Pavement designs are analyzed using an iterative process based on analysis software results for trial pavement structures proposed by the designer. A trial design is analyzed for adequacy against input performance criteria. The output of the analysis software is a prediction of distresses and smoothness against set reliability values. If the predictions do not meet the desired performance criteria at the given reliability, the trial design is revised and the evaluation is repeated.

The analysis software used in this study is DARWIN-ME from the American Association of State Highway and Transportation Officials (AASHTO). DARWIN-ME analysis is based upon the AASHTO Mechanistic-Empirical Pavement Design Guide.

The effect of CoTE on pavement performance using DARWIN-ME analysis is summarized in the tables below. CRCP with an analysis period of 50 years was evaluated for three climate regions. The objective is to determine the minimum thickness of concrete pavement that will meet the performance requirements defined by the Caltrans Highway Design Manual. JPCP with an analysis period of 40 years was evaluated for the same three climate regions. The JPCP was evaluated for a joint spacing of 13.5 and 12.5 feet.

CRCP Thickness

CoTE	Minimum Thickness to Meet Performance Thresholds (in.)		
	South Coast	Inland Valley	High Mountain
3.0	8	8	10^{B}
3.5	8	8	10^{B}
4.0	8	9^{B}	11^{B}
4.5	8	10^{B}	11^{B}
5.0	9^{B}	10^{B}	11^{B}
5.5	10^{B}	10^{B}	12^{B}
6.0	10^{B}	11^{B}	12^{B}
6.5	10^{B}	11^{B}	12^{B}
7.0	11^{B}	11^{B}	12^{B}
7.5	11^{B}	11^{B}	13^{B}
8.0	11^{B}	12^{B}	13^{B}

Minimum thickness to prevent: A-Failure of IRI limit (160 in/mi), B-Failure of punchout limit (1/mi)

JPCP Thickness with 13.5 ft joint spacing and 1.5 in. dia. dowels for thickness ≥11 in.

CoTE	Minimum Thickness to Meet Performance Thresholds (in.)		
	South Coast	Inland Valley	High Mountain
3.0	8[C]	9[C]	11[A]
3.5	9[C]	9[C]	11[A]
4.0	9[C]	9[C]	12[A]
4.5	9[C]	10[C]	13[A]
5.0	9[A,C]	11[B]	14[A]
5.5	11[B,C]	12[C]	16[A]
6.0	12[C]	14[C]	17[A,B]
6.5	14[C]	15[C]	20[A,B]
7.0	14[C]	15[C]	N/A
7.5	15[C]	16[C]	N/A
8.0	15[C]	16[B,C]	N/A

Minimum thickness to prevent: A-Failure of IRI limit (160 in/mi), B-Failure of mean joint faulting (0.10 in), C- Failure of transverse cracking (10%)

JPCP Thickness with 12.5 ft joint spacing and 1.5 in. dia. dowels for thickness ≥11 in.

CoTE	Minimum Thickness to Meet Performance Thresholds (in.)		
	South Coast	Inland Valley	High Mountain
3.0	8[C]	8[C]	10[A]
3.5	8[C]	9[C]	11[C]
4.0	9[C]	9[C]	11[C]
4.5	9[C]	9[C]	13[A]
5.0	9[C]	10[C]	14[A]
5.5	11[C]	12[C]	15[A]
6.0	12[C]	14[C]	16[A]
6.5	14[C]	15[C]	18[A]
7.0	14[C]	15[C]	20[A,B]
7.5	15[C]	16[C]	N/A
8.0	15[C]	16[C]	N/A

Minimum thickness to prevent: A-Failure of IRI limit (160 in/mi), B-Failure of mean joint faulting (0.10 in), C- Failure of transverse cracking (10%)

Conclusions

The results from this study compare favorably with the results obtained by the University of California Pavement Research Center (UCPRC) in a report prepared for the Transportation Research Board. UCPRC used the testing method based on AASHTO TP-60. CoTE values obtained from 74 cores ranges from 4.5 to 6.7 microstrain/°F. Specimens from four Caltrans Districts were compared and it was concluded that concretes in the coastal region have lower CTE compared to concretes in the north, south, and valley areas. CTE values from contiguous pavement sections up to 6 miles long reveal a typical variability of approximately 0.5 microstrain/°F.

The Caltrans study collected data from 312 cast specimens and drilled cores from 25 construction projects from 10 Districts. Six different testing laboratories were used including equipment at the Transportation Laboratory (TRANSLAB). Caltrans used the updated testing method based on AASHTO TP-336. The CoTE values range from 3.605 to 5.583 microstrain/°F. The overall average value for CoTE is 4.578 microstrain/°F with a variability of approximately 0.5 microstrain/°F.

Based on the results of the testing:

1 – A CoTE of 5.5 is very achievable in California

2 - There is a loss of performance above 5.5 so allowing higher values would create added cost based on added thickness required when using higher CoTE.

3 - There is some variability in the test results which can be compensated for by testing mix several times and take average.

The department is planning to conduct round robin testing to check variability of results from different testing laboratories using the same samples.

Caltrans is pursuing the recommendation for using CoTE data to optimize pavement design. The department has decided against implementing CoTE as an acceptance criteria for field qualification of concrete mix designs.

JPCP South Coast CTE 5.5 Thk 11 JS 12.5

File Name: D:\2013\PvD\SC_12.5\JPCP South Coast CTE 5.5 Thk 11 JS 12.5.dgpx

Design Inputs

Design Life: 40 years
Design Type: Jointed Plain Concrete Pavement (JPCP)

Existing construction: -
Pavement construction: September, 2006
Traffic opening: October, 2006

Climate Data Sources (Lat/Lon): 32.572, -116.979

Design Structure

Layer type	Material Type	Thickness (in.):
PCC		11.0
Stabilized		6.0
NonStabilized		6.0
Subgrade		Semi-infinite

Joint Design:

Joint spacing (ft)	12.5
Dowel diameter (in.)	1.50
Slab width (ft)	12.0

Traffic

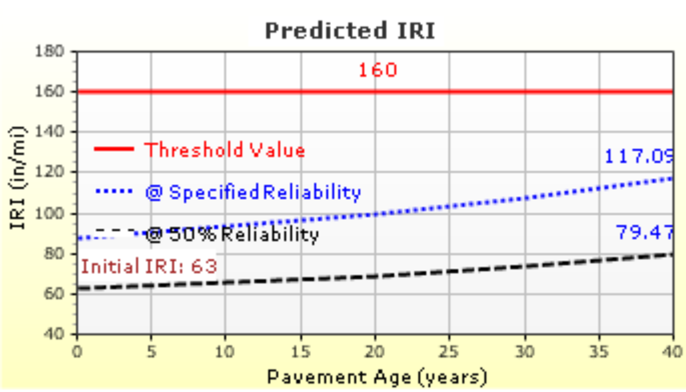
Age (year)	Heavy Trucks (cumulative)
2006 (initial)	9,000
2026 (20 years)	46,496,800
2046 (40 years)	148,377,000

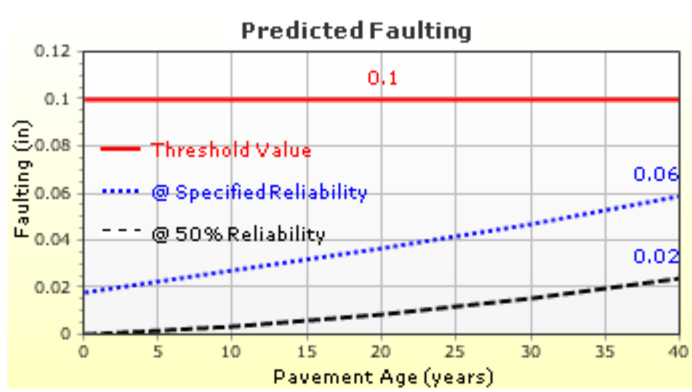
Design Outputs

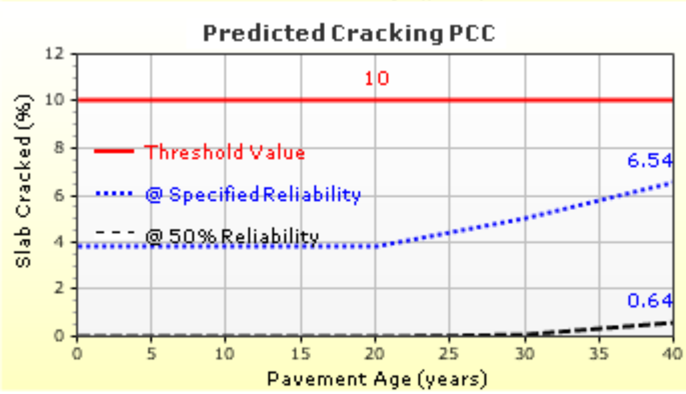
Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	160.00	117.09	90.00	99.70	Pass
Mean joint faulting (in.)	0.10	0.06	90.00	99.73	Pass
JPCP transverse cracking (percent slabs)	10.00	6.54	90.00	97.90	Pass

Distress Charts



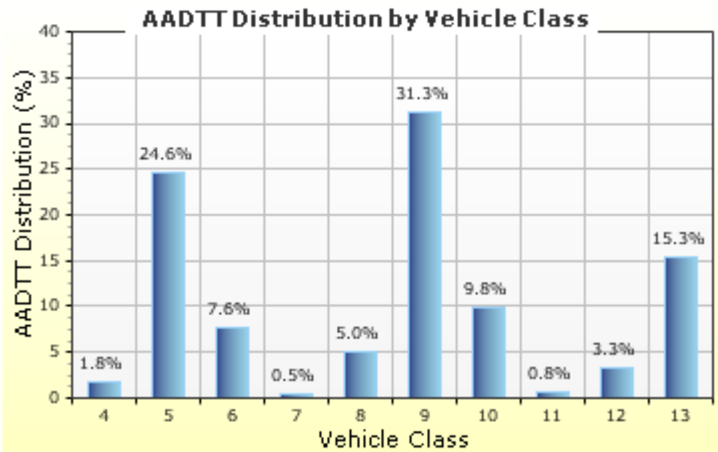


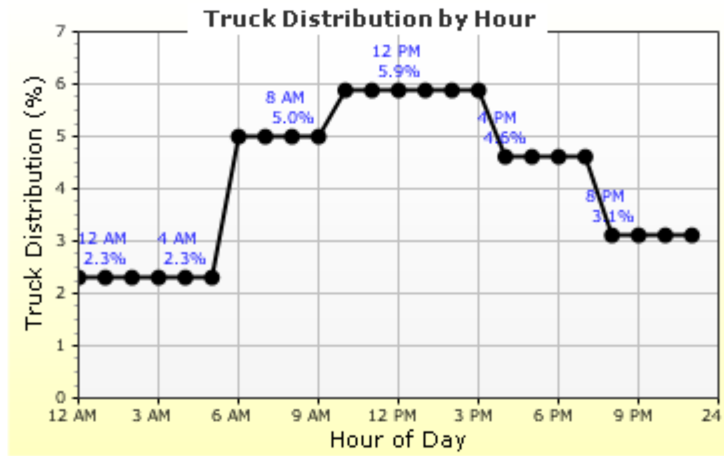


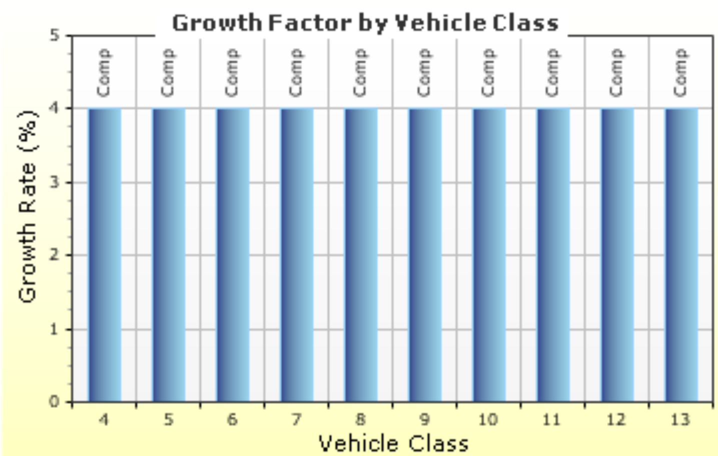
Traffic Inputs

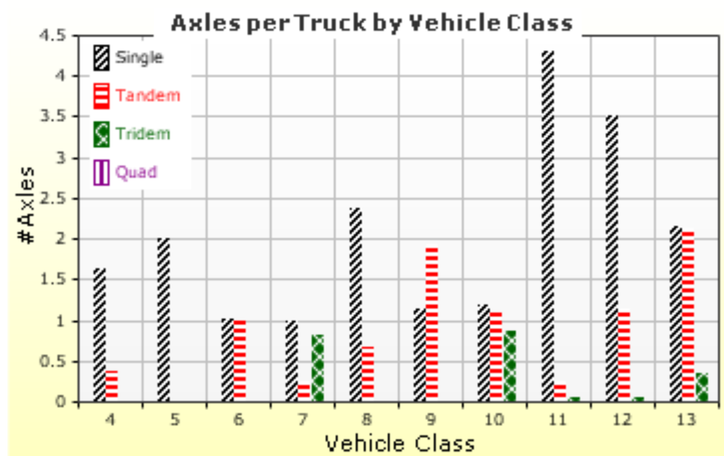
Graphical Representation of Traffic Inputs

Initial two-way AADTT:	9,000	Percent of trucks in design direction (%):	50.0
Number of lanes in design direction:	2	Percent of trucks in design lane (%):	95.0
		Operational speed (mph)	65.0

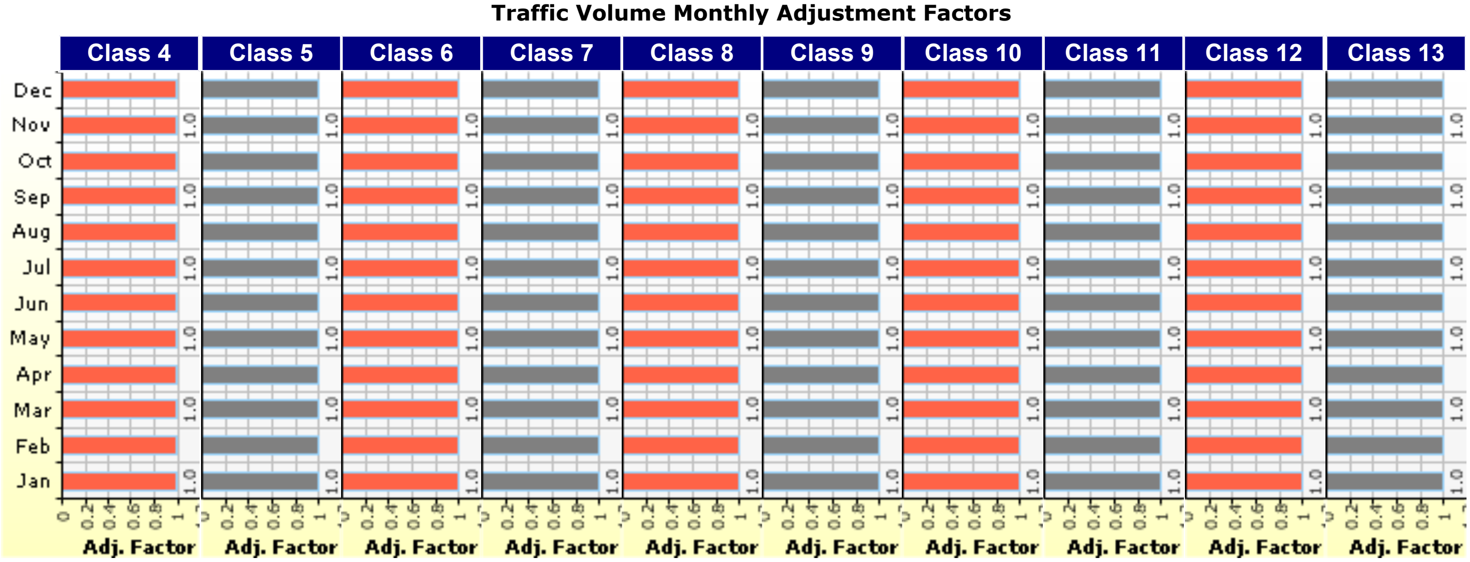








Traffic Volume Monthly Adjustment Factors



Tabular Representation of Traffic Inputs

Volume Monthly Adjustment Factors

Level 3: Default MAF

Month	Vehicle Class									
	4	5	6	7	8	9	10	11	12	13
January	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
February	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
March	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
April	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
May	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
June	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
July	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
August	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
September	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
October	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
November	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
December	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Distributions by Vehicle Class

Vehicle Class	AADTT Distribution (%) (Level 3)	Growth Factor	
		Rate (%)	Function
Class 4	1.8%	4%	Compound
Class 5	24.6%	4%	Compound
Class 6	7.6%	4%	Compound
Class 7	0.5%	4%	Compound
Class 8	5%	4%	Compound
Class 9	31.3%	4%	Compound
Class 10	9.8%	4%	Compound
Class 11	0.8%	4%	Compound
Class 12	3.3%	4%	Compound
Class 13	15.3%	4%	Compound

Truck Distribution by Hour

Hour	Distribution (%)	Hour	Distribution (%)
12 AM	2.3%	12 PM	5.9%
1 AM	2.3%	1 PM	5.9%
2 AM	2.3%	2 PM	5.9%
3 AM	2.3%	3 PM	5.9%
4 AM	2.3%	4 PM	4.6%
5 AM	2.3%	5 PM	4.6%
6 AM	5%	6 PM	4.6%
7 AM	5%	7 PM	4.6%
8 AM	5%	8 PM	3.1%
9 AM	5%	9 PM	3.1%
10 AM	5.9%	10 PM	3.1%
11 AM	5.9%	11 PM	3.1%
		Total	100%

Axle Configuration

Traffic Wander	
Mean wheel location (in.)	18
Traffic wander standard deviation (in.)	10
Design lane width (ft)	12

Axle Configuration	
Average axle width (ft)	8.5
Dual tire spacing (in.)	12
Tire pressure (psi)	120

Average Axle Spacing	
Tandem axle spacing (in.)	51.6
Tridem axle spacing (in.)	49.2
Quad axle spacing (in.)	49.2

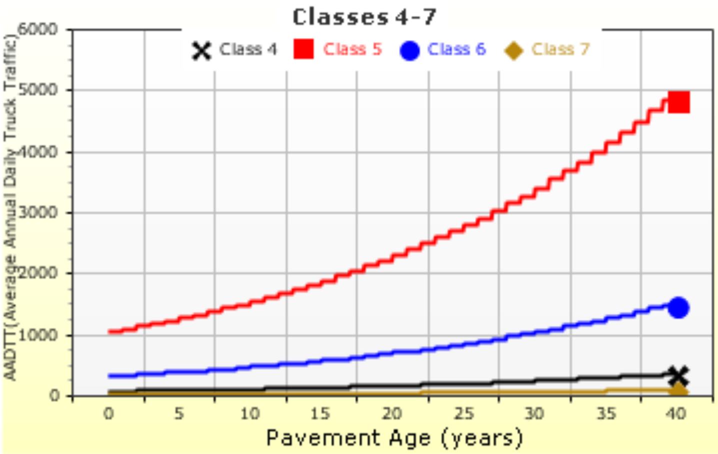
Wheelbase			
Axle Type / Value Type	Short	Medium	Long
Average spacing of axles (ft)	12	15	18
Percent of Trucks (%)	33	33	34

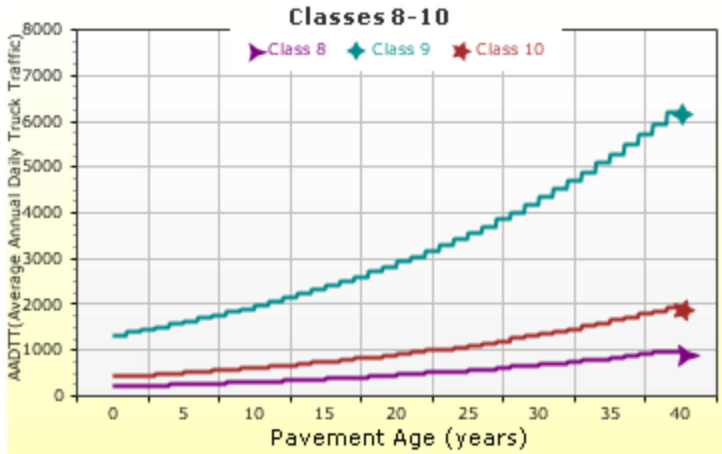
Number of Axles per Truck

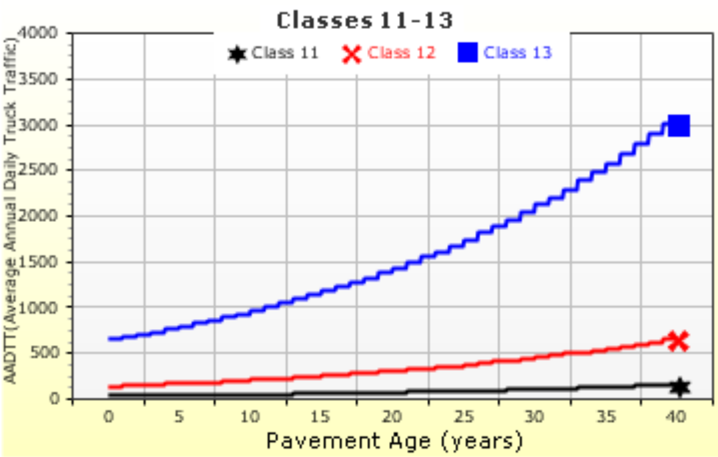
Vehicle Class	Single Axle	Tandem Axle	Tridem Axle	Quad Axle
Class 4	1.62	0.39	0	0
Class 5	2	0	0	0
Class 6	1.02	0.99	0	0
Class 7	1	0.26	0.83	0
Class 8	2.38	0.67	0	0
Class 9	1.13	1.93	0	0
Class 10	1.19	1.09	0.89	0
Class 11	4.29	0.26	0.06	0
Class 12	3.52	1.14	0.06	0
Class 13	2.15	2.13	0.35	0

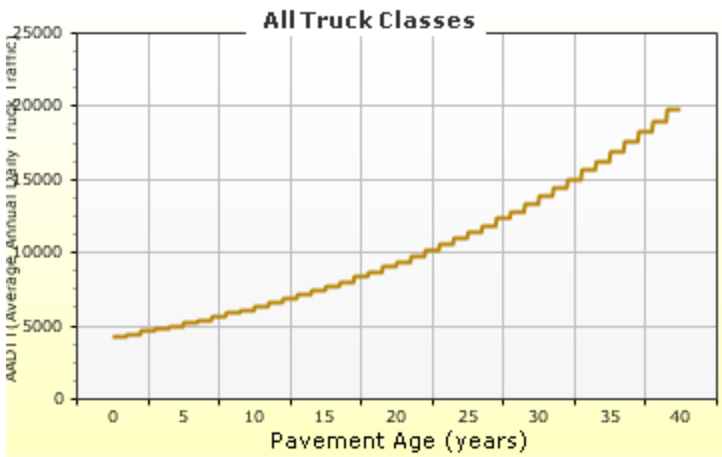
AADTT (Average Annual Daily Truck Traffic) Growth

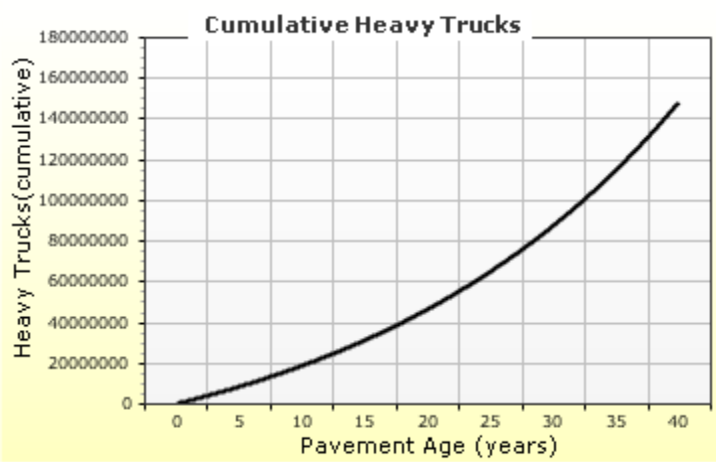
*** Traffic cap is not enforced**







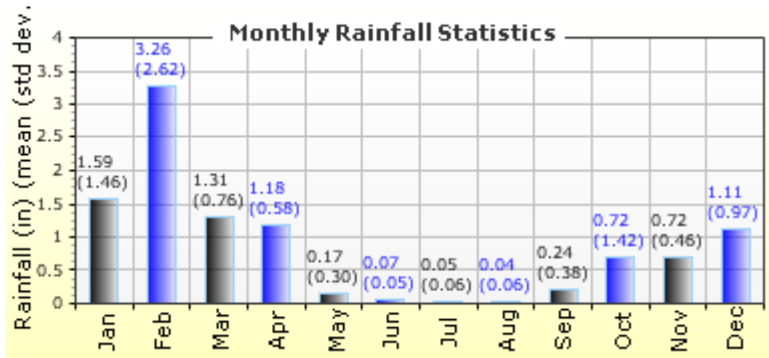




Climate Inputs

Climate Data Sources:

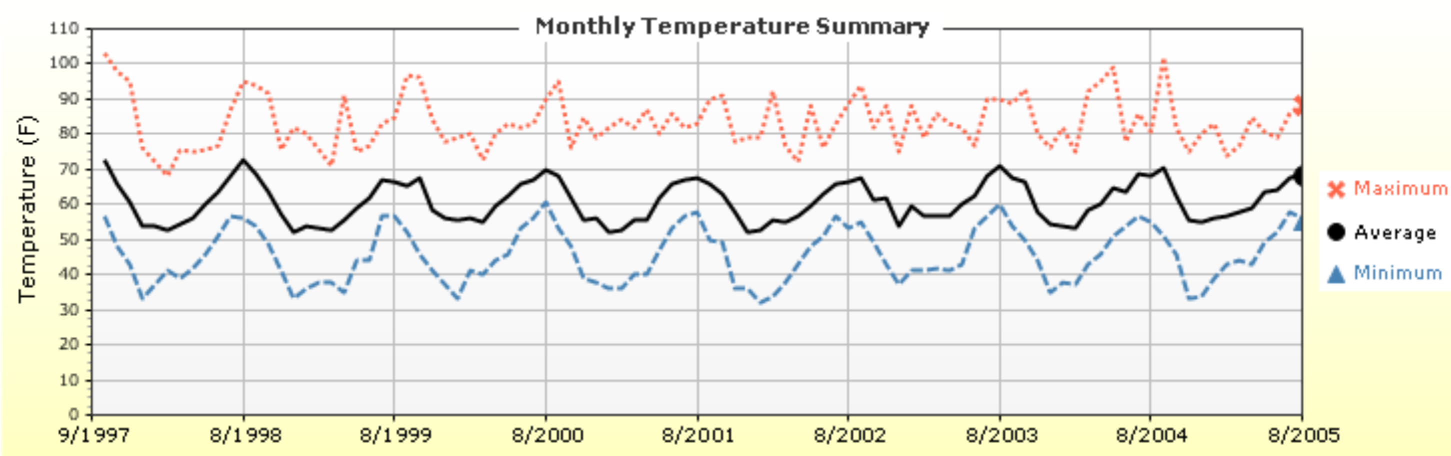
Climate Station Cities:	Location (lat lon elevation(ft))
SAN DIEGO, CA	32.57200 -116.97900 520

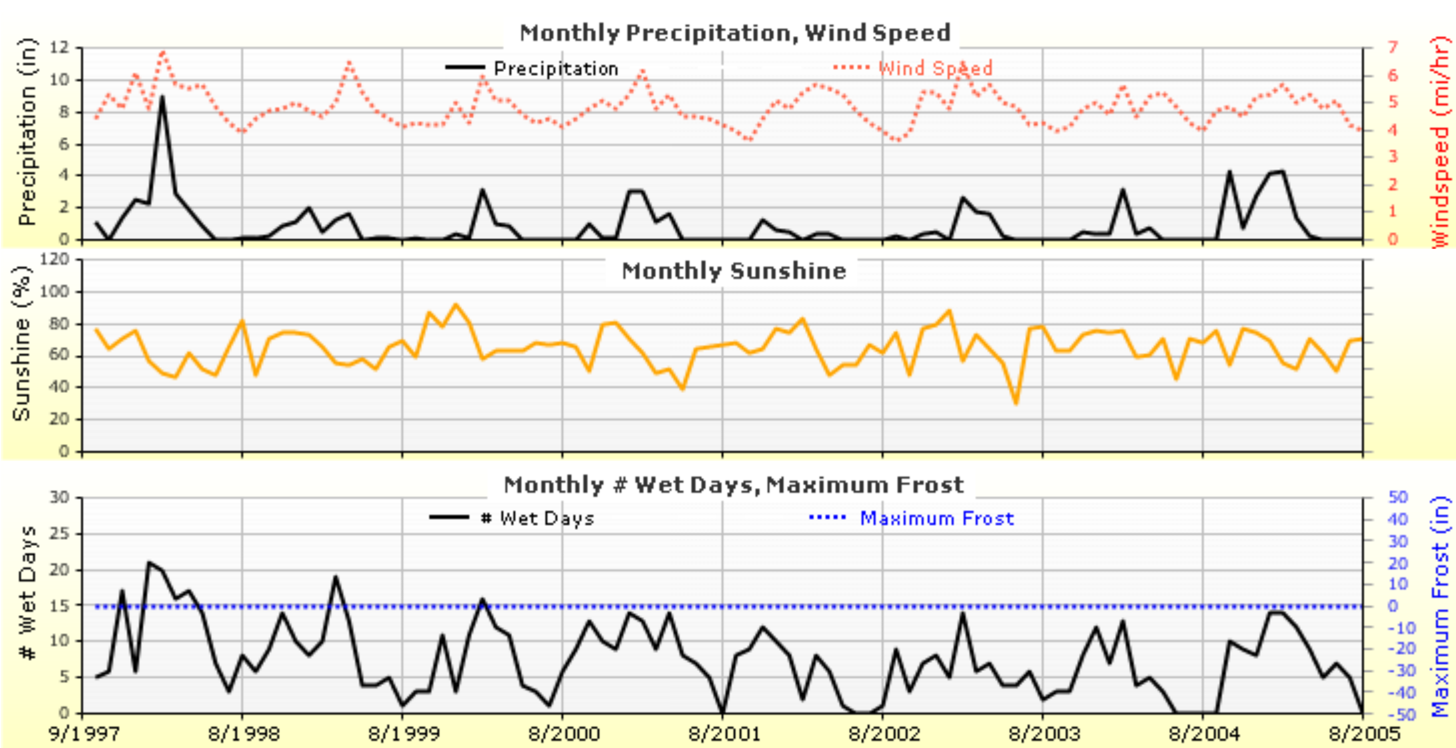


Annual Statistics:

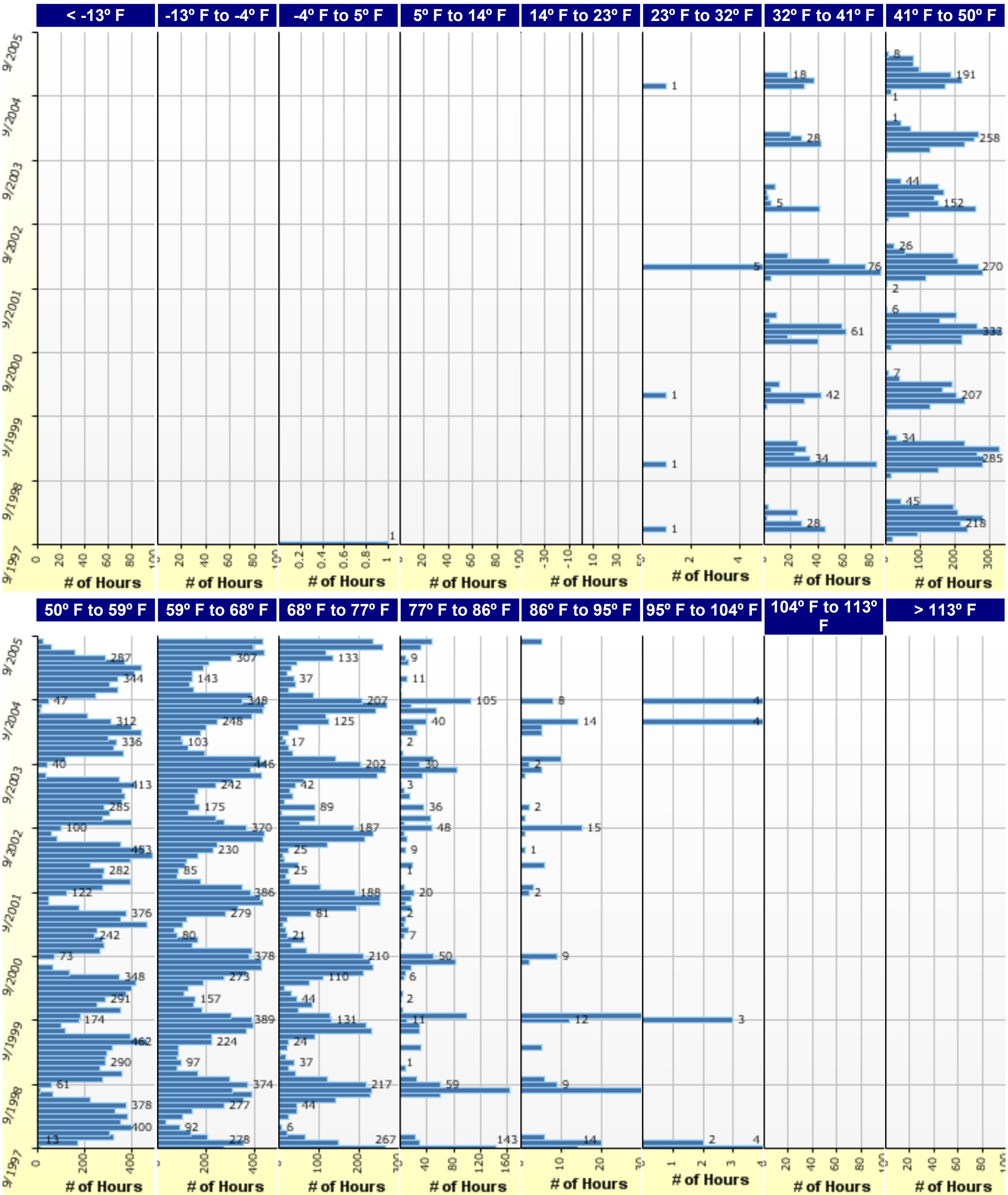
Mean annual air temperature (ºF)	60.75
Mean annual precipitation (in.)	10.48
Freezing index (ºF - days)	0.00
Average annual number of freeze/thaw cycles:	0.00
Water table depth (ft)	20.00

Monthly Climate Summary:





Hourly Air Temperature Distribution by Month:



Design Properties

JPCP Design Properties

Structure - ICM Properties	
PCC surface shortwave absorptivity	0.85

Doweled Joints	
Is joint doweled ?	True
Dowel diameter (in.)	1.50
Dowel spacing (in.)	12.00

Tied Shoulders	
Tied shoulders	True
Load transfer efficiency (%)	70.00

PCC joint spacing (ft)	
Is joint spacing random ?	False
Joint spacing (ft)	12.50

Widened Slab	
Is slab widened ?	False
Slab width (ft)	12.00

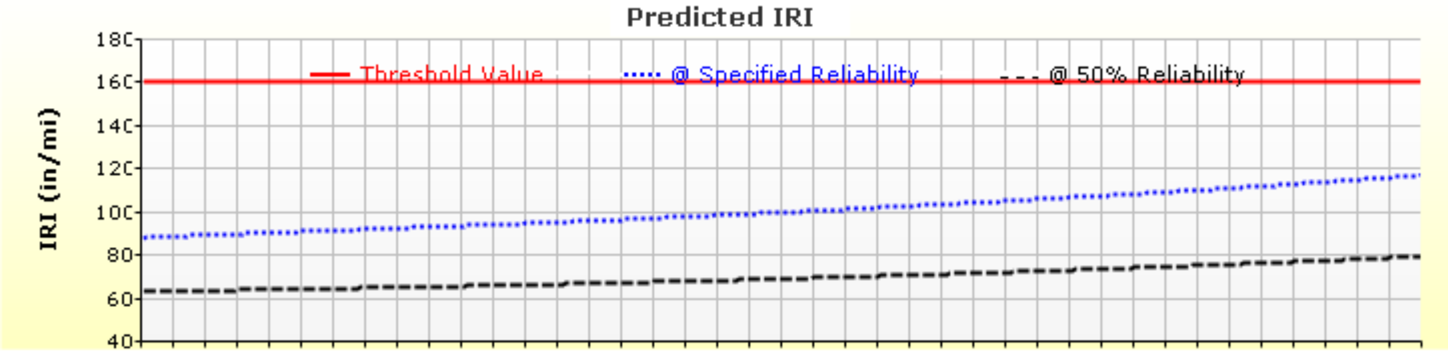
PCC-Base Contact Friction	
PCC-Base full friction contact	True
Months until friction loss	245.00

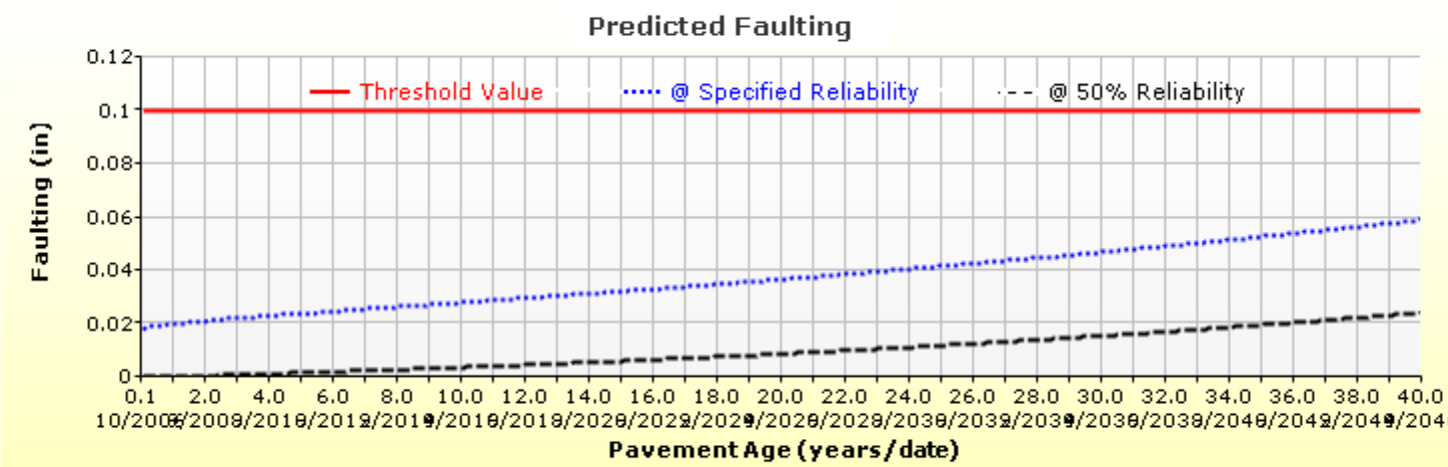
Sealant type	Other(Including No Sealant... Liquid... Silicone)

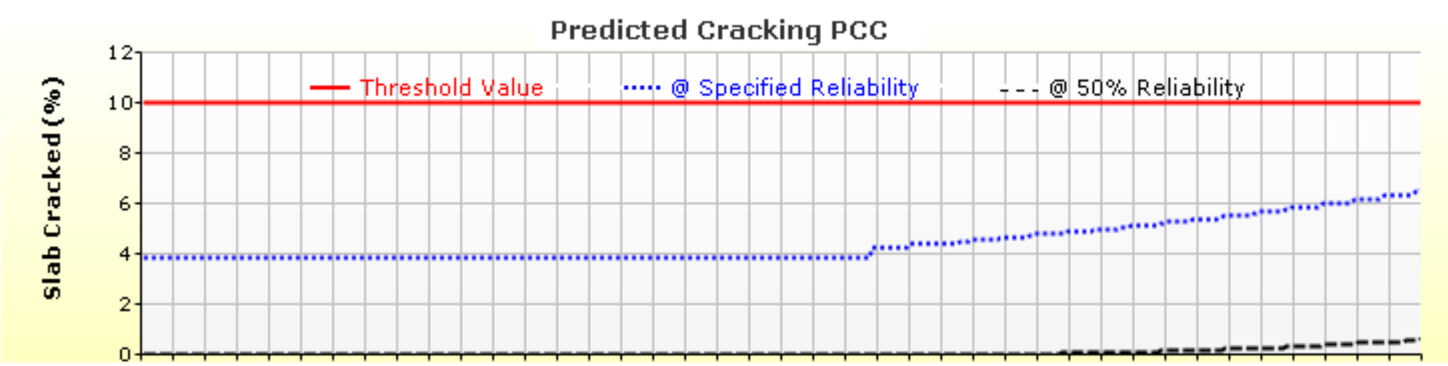
Erodibility index	5

Permanent curl/warp effective temperature difference (ºF)	-10.00

Analysis Output Charts

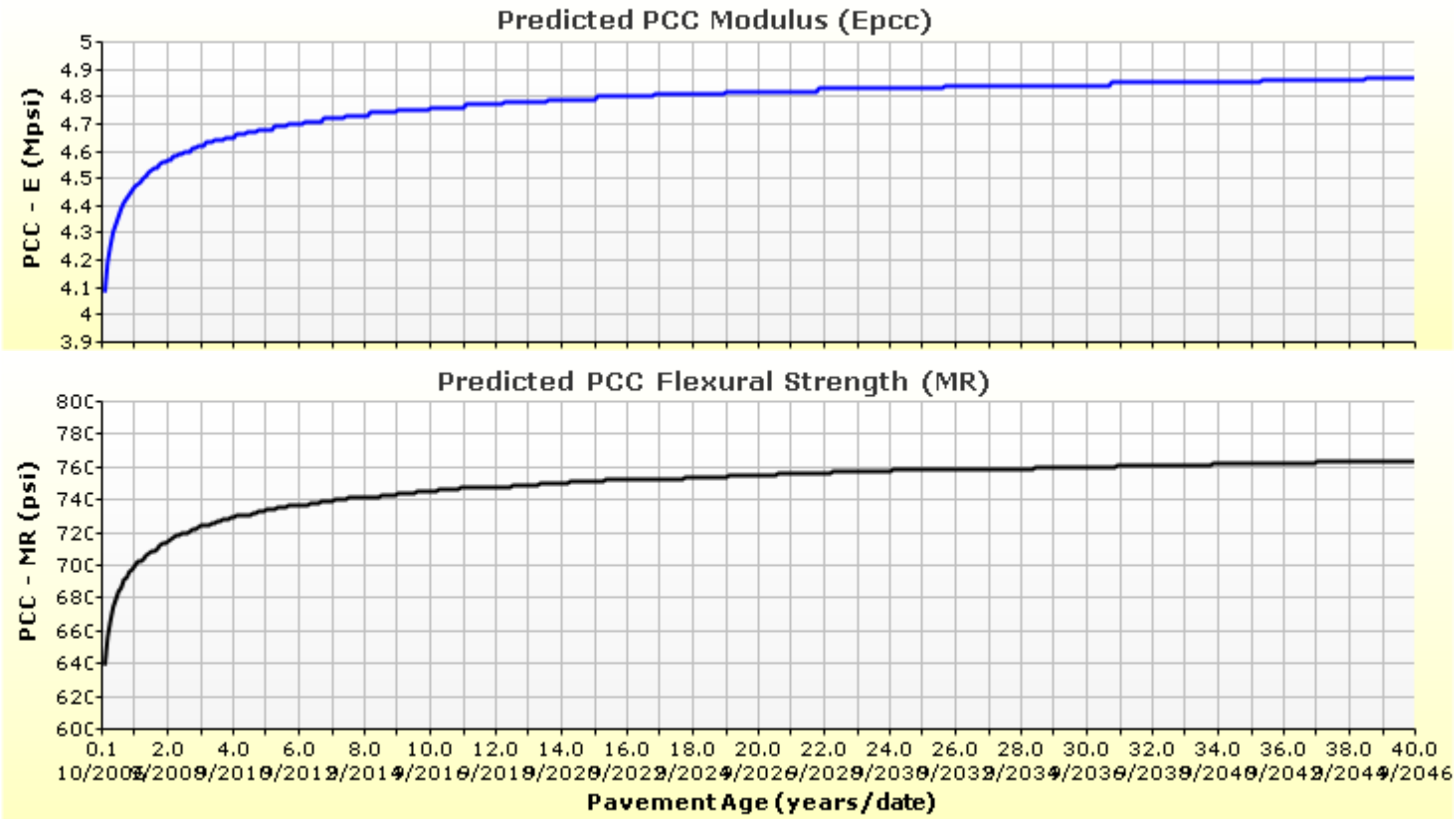


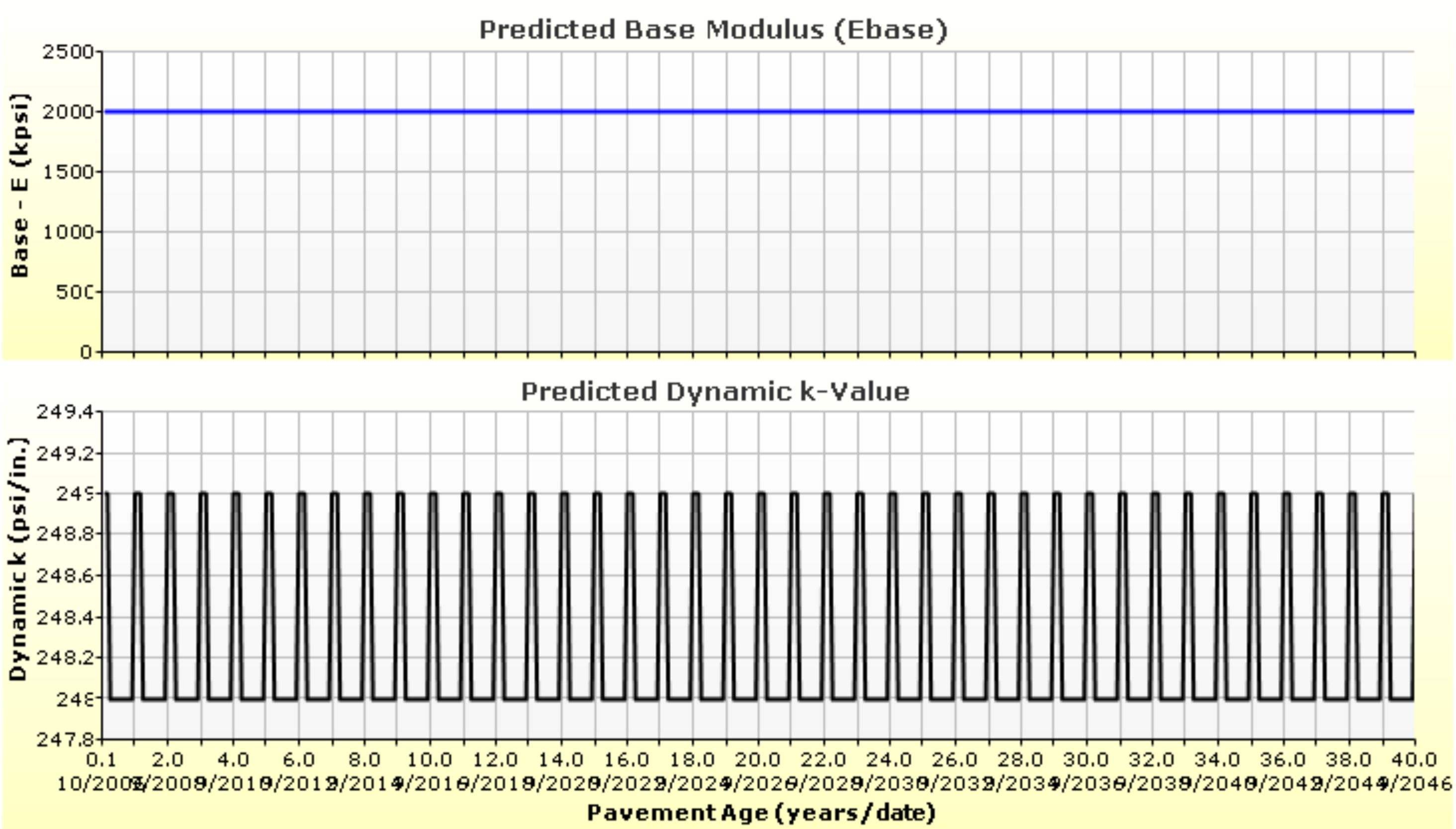


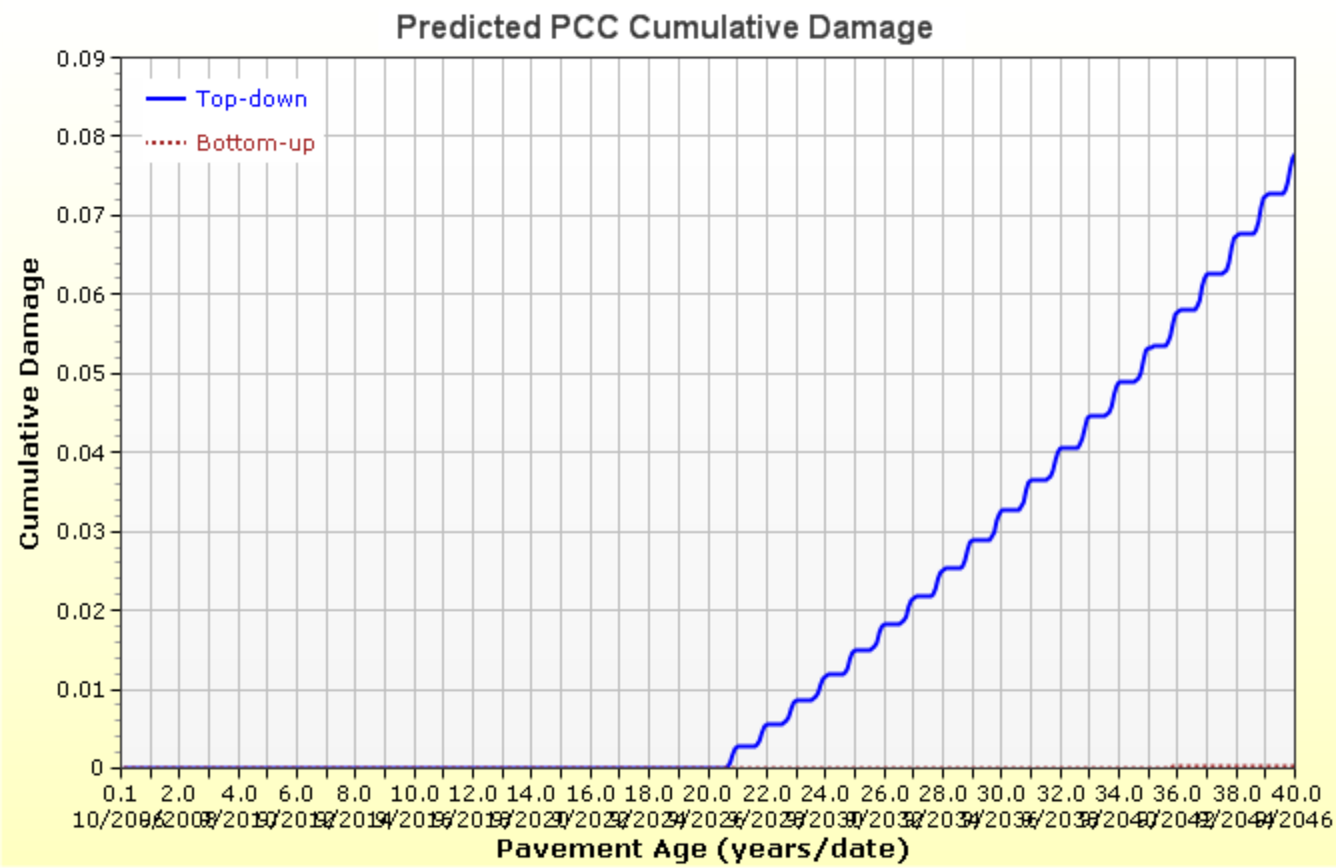


JPCP South Coast CTE 5.5 Thk 11 JS 12.5

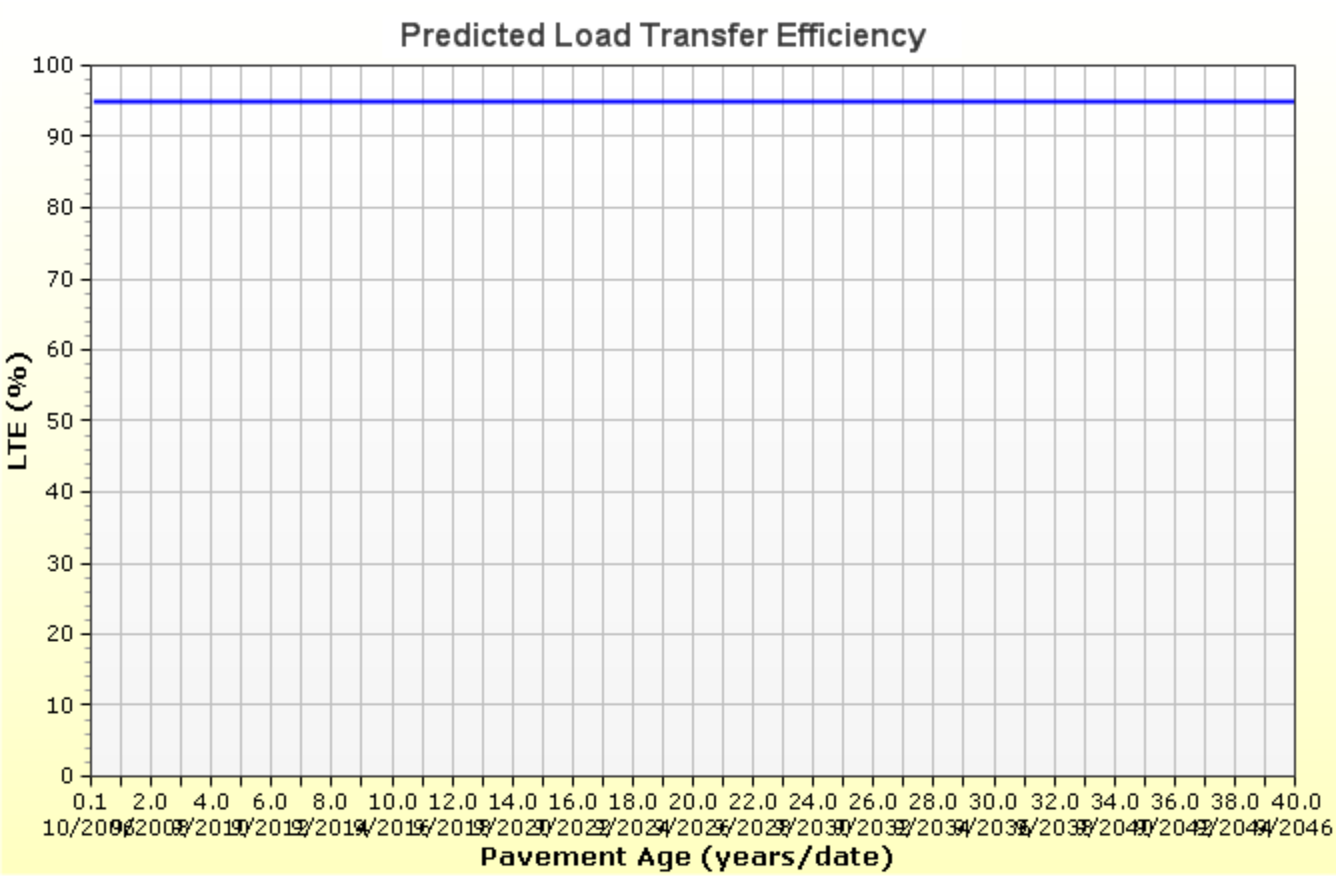
File Name: D:\2013\PvD\SC_12.5\JPCP South Coast CTE 5.5 Thk 11 JS 12.5.dgpx







Predicted PCC Cumulative Damage
Top-down
Bottom-up
Cumulative Damage
Pavement Age (years/date)



Predicted Load Transfer Efficiency
LTE (%)
Pavement Age (years/date)

Layer Information

Layer 1 PCC

PCC	
Thickness (in.)	11.0
Unit weight (pcf)	150.0
Poisson's ratio	0.2

Thermal	
PCC coefficient of thermal expansion (in./in./ºF x 10^-6)	5.5
PCC thermal conductivity (BTU/hr-ft-ºF)	1.25
PCC heat capacity (BTU/lb-ºF)	0.28

Mix		
Cement type		Type II (2)
Cementitious material content (lb/yd^3)		648
Water to cement ratio		0.42
Aggregate type		Limestone (1)
PCC zero-stress temperature (ºF)	Calculated Internally?	False
	User Value	100
	Calculated Value	-
Ultimate shrinkage (microstrain)	Calculated Internally?	False
	User Value	537.0
	Calculated Value	-
Reversible shrinkage (%)		50
Time to develop 50% of ultimate shrinkage (days)		35
Curing method		Curing Compound

PCC strength and modulus (Input Level: 3)

28-Day PCC modulus of rupture (psi)	625.0
28-Day PCC elastic modulus (psi)	3988512.9

Identifiers

Field	Value
Display name/identifier	
Description of object	
Author	
Date Created	10/14/2013 12:00:00 AM
Approver	
Date approved	10/14/2013 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 2 Sandwich/Fractured

Chemically Stabilized	
Layer thickness (in.)	6
Poisson's ratio	0.2
Unit weight (pcf)	150

Strength	
Elastic/resilient modulus (psi)	2000000

Thermal	
Heat capacity (BTU/lb-ºF).	0.28
Thermal conductivity (BTU/hr-ft-ºF)	1.25

Identifiers

Field	Value
Display name/identifier	
Description of object	
Author	
Date Created	1/2/2013 12:00:00 AM
Approver	
Date approved	1/2/2013 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 2	
User defined field 3	
Revision Number	0

Layer 3 Non-stabilized Base

Unbound	
Layer thickness (in.)	6.0
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
25000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	
Description of object	
Author	
Date Created	1/2/2013 12:00:00 AM
Approver	
Date approved	1/2/2013 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	6.0
Plasticity Index	1.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	127.2
Saturated hydraulic conductivity (ft/hr)	False	5.054e-02
Specific gravity of solids	False	2.7
Optimum gravimetric water content (%)	False	7.4

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	7.2555
bf	1.3328
cf	0.8242
hr	117.4000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	8.7
#100	
#80	12.9
#60	
#50	
#40	20.0
#30	
#20	
#16	
#10	33.8
#8	
#4	44.7
3/8-in.	57.2
1/2-in.	63.1
3/4-in.	72.7
1-in.	78.8
1 1/2-in.	85.8
2-in.	91.6
2 1/2-in.	
3-in.	
3 1/2-in.	97.6

Layer 4 Subgrade

Unbound	
Layer thickness (in.)	Semi-infinite
Poisson's ratio	0.35
Coefficient of lateral earth pressure (k0)	0.5

Modulus (Input Level: 3)

Analysis Type:	Modify input values by temperature/moisture
Method:	Resilient Modulus (psi)

Resilient Modulus (psi)
16000.0

Use Correction factor for NDT modulus?	-
NDT Correction Factor:	-

Identifiers

Field	Value
Display name/identifier	
Description of object	
Author	
Date Created	1/2/2013 12:00:00 AM
Approver	
Date approved	1/2/2013 12:00:00 AM
State	
District	
County	
Highway	
Direction of Travel	
From station (miles)	
To station (miles)	
Province	
User defined field 2	
User defined field 3	
Revision Number	0

Sieve

Liquid Limit	50.0
Plasticity Index	29.0
Is layer compacted?	False

	Is User Defined?	Value
Maximum dry unit weight (pcf)	False	120.8
Saturated hydraulic conductivity (ft/hr)	False	6.832e-06
Specific gravity of solids	False	2.7
Optimum gravimetric water content (%)	False	10.6

User-defined Soil Water Characteristic Curve (SWCC)	
Is User Defined?	False
af	100.4941
bf	0.7343
cf	0.2680
hr	500.0000

Sieve Size	% Passing
0.001mm	
0.002mm	
0.020mm	
#200	27.4
#100	
#80	32.0
#60	
#50	
#40	37.1
#30	
#20	
#16	
#10	47.6
#8	
#4	55.4
3/8-in.	72.4
1/2-in.	78.1
3/4-in.	85.3
1-in.	89.1
1 1/2-in.	94.6
2-in.	97.0
2 1/2-in.	
3-in.	
3 1/2-in.	100.0

Calibration Coefficients

PCC Faulting

$$C_{12} = C_1 + (C_2 * FR^{0.25})$$
$$C_{34} = C_3 + (C_4 * FR^{0.25})$$
$$FaultMax_0 = C_{12} * \delta_{curling} * \left[\log(1 + C_5 * 5.0^{EROD}) * \log\left(P_{200} * \frac{WetDays}{p_s}\right)\right]^{C_6}$$
$$FaultMax_i = FaultMax_0 + C_7 * \sum_{j=1}^{m} DE_j * \log(1 + C_5 * 5.0^{EROD})^{C_6}$$
$$\Delta Fault_i = C_{34} * (FaultMax_{i-1} - Fault_{i-1})^2 * DE_i$$
$$C_8 = DowelDeterioration$$

C1: 1.0184	C2: 0.91656	C3: 0.0021848	C4: 0.000883739
C5: 250	C6: 0.4	C7: 1.83312	C8: 400
PCC Reliability Faulting Standard Deviation			
POW(0.0097*FAULT,0.5178)+0.014			

IRI-jpcp

C1 - Cracking	C1: 0.8203	C2: 0.4417
C2 - Spalling	C3: 1.4929	C4: 25.24
C3 - Faulting	**Reliability Standard Deviation**	
C4 - Site Factor	5.4	

PCC Cracking

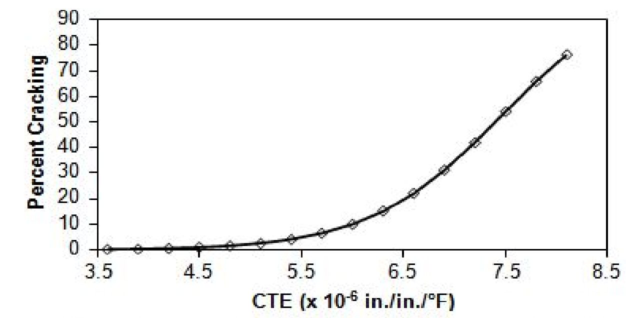
$$\log(N) = C1 \cdot \left(\frac{MR}{\sigma}\right)^{C2}$$

$$CRK = \frac{100}{1 + C4\, FD^{C5}}$$

Fatigue Coefficients		**Cracking Coefficients**	
C1: 2	C2: 1.22	C4: 1	C5: -1.98
PCC Reliability Cracking Standard Deviation			
POW(5.3116*CRACK,0.3903) + 2.99			

Concrete Coefficient of Thermal Expansion Report
Comments and Response Table

Commentor	Page	comment	Pavement's Response
Ken Darby	General	As previously discussed, the precision and bias of the CoTE test needs to be established before design and specification limits are set (e.g. design CoTE requirement – precision and bias = max CoTE). FHWA is in the process of determining the precision and bias according to Pavements.	The precision and bias determination of the COTE test is beyond the scope of this report.
Ken Darby	General	The specifications should set required CoTE values and allow bidders/contractors to consider these in their bid. No mitigation measures (e.g. increased thickness, shorter slabs, etc.) should be allowed for materials not meeting required CoTE values. Though, perhaps a deductive percentage could be considered in the specification if the CoTE values were slightly over the requirement. This deductive percentage would need to be established based on a reduced design life/life cycle cost analysis.	The deduction or other measure can be established once the COTE requirement is adopted into the specification.
Ken Darby	General	ME design results for JPCP seem very dependent on CoTE values and indicate thicker slabs may be needed across the board. Prior to adopting the expensive option of increasing slab thicknesses, it may be money well spent to evaluate existing slab performance against CoTE samples to verify ME design results. Pavements has indicated that UPCRC(?) is available to perform such an analysis.	UCPRC may have a follow up study for COTE. The discussion for the contract is in progress.
Ken Darby	1	Within the "purpose" section it is stated that this study has shown that higher values of CoTE have a negative impact on long-term pavement performance. I do not believe this study has shown this definitively as the ME design results have not been verified with respect to CoTE variability. There may be other research to that effect, but it was not referenced.	This report show the negative impact of higher value of COTE using AASTHO-MEPDG and other parameter in constant value. It is difficult to predict any other type of research in the future and the result.
Ken Darby	29	Appears to be an error with regard to delta temperature 2 calculations. Not sure if this was a typo or used in subsequent calculations.	It does look an error from Twinning lab.
Ken Darby	31	ME design results for CRCP thickness as a function of CoTE and environmental location is not that sensitive. A 12" thickness requirement for CRCP regardless of environmental location would appear to resolve CoTE concerns based on CoTE evaluations to date and expected precision and bias amount.	Correct, the thicker section has less sensitivity but does cost more to construct.
Ken Darby	32	JPCP thickness does not appear to be greatly affected by joint spacing alone	Correct, other factor
Ken Darby		JPCP thickness appears to be very sensitive to both CoTE values and environmental location via ME design results.	Correct
Ken Darby		Given these tables and a design CoTE value of 6.0, high mountain regions should receive a 20" thickness, inland valley 16" thickness and south coast 15" thickness. These are considerably thicker JPCP sections in comparison to JPCP shown in the highway design manual (HDM). Seems appropriate to verify ME design results reflect pavement performance needs through a separate evaluation of CoTE sample results to known pavement performance.	The HDM thickness design data were based on the initial development of the ME-PDG, and various thickness of the base or other variables. This report is based on the latest Darwin-ME or AASTHO-MEPDG. Other than joint spacing, slab thickness, COTE number and climate region, all others variables have been kept constant including the base type and thickness. There for the thickness of the JPCP should not be compared between this report and HDM.
James Sagar		The report states the average California aggregate CoTE value as 4.57 microstrain/degree F, and a max of 5.583; since the AASHTO recommended CoTE limit is 5.5, why is CoTE viewed as a relevant factor for California aggregates?	This report contain a maximum value of 5.62 (AASHTO T336) and there is evidence that we still have CoTE value up to 6.7 (AASHTO TP-60) study conducted by UCPRC in 2007.
James Sagar		With California aggregates testing at low CoTE values, why not modify the spec to exclude CoTE requirements for all types of paving?	It is true the majority of the COTE value in the report do not show a high value of COTE, but it is not necessary 100% guaranteed that a high COTE value does not exist in California. For example, Quartzite aggregates has a high value of COTE between 5.6-6.7 and exist in a lot of places in California.

Commentor	Page	comment	Pavement's Response
James Sagar	1	in the first paragraph, there is reference to the “AASHTO recommended CoTE value of 5.5”. Is documentation available that shows this recommendation? Would be helpful to cite a source here.	The paragraph is modified, reference is shown. The information is shown on the graph to the bottom.  FIGURE 4 Effect of CTE on predicted percentage of slabs cracked.
James Sagar	33	Regarding Result #2 on Page 33, it is unclear from the data on Pages 31-32 how a critical value of 5.5 was determined. Seems to be a direct correlation between CoTE and Minimum Thickness for all values. More analysis may be needed here	The intent of the information on page 31-33 is not for the determination for the limit value of 5.5. The intent is to show the increament of the slab thickness when a higher COTE value is used.
James Sagar	33	Regarding Result #3, is the variability in the data a cause for concern? Is there a hypothesis as to the cause for this variability in the test results? May be best to include here, in case a test result is questioned during project delivery.	The variability of test data may create concern if it exceeding the confident level needed. There for taking average for several sample will reduce this issue. Currently there is no clear explanation the cause of this variabiltiy, another scoping document can be written for that matter.
James Sagar	33	Also, on Page 33, the final sentence indicates that “The Department has decided against implementing CoTE as an acceptance criteria”. It is recommended, based on the data presented in the report indicating that very few test results approached or exceeded the 5.5 value, that CoTE be eliminated from the specifications entirely if it is deemed unnecessary as a criteria for acceptance. It appears from the data that there is little evidence to show that CoTE is of significant concern Statewide.	The report shows the COTE test result from various project and location in California, and several run from the AASHTO-MEPDG showing the effect of COTE with various slab thicness or spacing.
Charley Rea		The author(s) are to be complimented on the report. It fills a need and presents considerable test data that will be of great use to many designers.	Thank you, we are keep adding the data as they arrive.
Charley Rea		I make no suggestions for pages 30 and 31 since I am not qualified to judge.	OK
Charley Rea		In the introduction it is noted that the UCPRC study used 74 cores and the Caltrans study “…304 cast specimens and from 24 construction sites…” For consistency the total number of specimens should be noted.	We do differentiate sample from cores or specimens.
Charley Rea		Some of the statistics (e.g. mean values) are reported with values such as 5.123 microstrain per degree F. I think the data do not justify this “precision” (equivalent to stating 1 part in10 -9)	This is just a result of statistical value.
Charley Rea		The CTE of aggregate (usually the biggest contributor to the total) depends upon its mineralogical constitution. . In Table 1 it would be helpful to have the “geological” description of the locations of the quarries (presumably also the location of the aggregates employed) augmented by noting (if possible) the mineralogical analysis (most quarries have at least some of this type of data) exemplified by the Table below o(from LTPP). Best of all to give both.	The data we can get from USGS is noted on the table. The USGS do not have any additional information. Any other detail data just indicate gravel and rock or others not significant.
Charley Rea		CTE varies with mix. But I could not find any data on the “volumetrics” (pardon me for using a term from our “dark side”) of the concrete mixtures tested. If true, this means that the mixes cannot be compared on any quantitative basis. Am I missing something?	The detail of the concrete mix is not included in this report.
Charley Rea		I do suggest a note that recognizes that the test value is not necessarily the value that will be exhibited in the field. The situation is similar to concrete compressive strength testing. The standard 28 day test gives a value that is useful for comparative and control purposes but it is known (though often forgotten) that the actual strength in the field is a function of many things and may be significantly different from f(28). The same is true here and designers need to note that a test value of 6 micro may in fact mean as much 9 micro in certain environments.	This test as anything else is the closest reference to what actually being built.
Charley Rea		Since I have put in my two cents I should offer more. I think this report would make the basis for a very useful paper (especially I fit includes the data from LTPP). I would be happy to assist Amy in drafting such paper. Perhaps others on CalCIMA Tech would also offer? From a lab person’s point of view I would like to see future research make tests on cement pastes and for individual pieces of aggregate (the latter is a challenge, especially for fine aggs., but could be tackled).	Thank you for the offer.